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14. ABSTRACT

This report reviews the second year of research on the diagnostic utility of psychophysiological indices that may predict the current and future functional efficiency of the soldier. The research focuses especially on the measurement of cerebral blood flow using transcranial Doppler sonography (TCD), together with additional indices including salivary cortisol and subjective state. Research at the University of Cincinnati has demonstrated that cerebral blood flow covaries with performance efficiency on a vigilance task and that phasic blood flow responses generated by a battery of short high-workload tasks can be used to predict future vigilance performance, particularly among observers who rate the workload of the vigilance task as low. In addition, these studies also demonstrated that high task-engagement in working with the short battery was predictive of superior vigilance performance, as were high task-focused coping and low avoidance coping strategies, and they verified the utility of TCD in monitoring performance in *auditory* as well as in visual sustained attention tasks. Research at Georgia State University, employing a simulated sentry task called " Watchkeeper", confirmed that cerebral blood flow covaries with performance efficiency on a sustained attention task and supported the utility of using TCD to predict the quality of sustained attention.

15. SUBJECT TERMS
Stress, cerebral bloodflow, performance, vigilance, sustained attention, fatigue, cortisol, individual differences, workload

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INTRODUCTION

Combat stress often disrupts performance efficiency and situation awareness during military operations. The assessment of fitness for duty in stressful environments requires techniques for monitoring the current functional efficiency of the soldier, along with techniques that will predict when a soldier will not be able to sustain performance on some future task. This report describes the accomplishments of the second year of a proposed three-year program of research that aims to investigate the diagnostic utility of psychophysiological indices that may predict current and future functional efficiency. The research focuses especially on the measurement of cerebral blood flow using transcranial Doppler sonography (TCD) together with additional indices using salivary cortisol and subjective stress state.

Two studies were completed at the University of Cincinnati. The first study was designed to compare cerebral blood flow, salivary cortisol, and subjective states as diagnostic predictors of sensory vigilance. The unique strategy employed in the study was the use of phasic psychophysiologial and stress measures secured from a battery of short high-workload tasks involving line detection, working memory, and psychomotor tracking to predict performance on a simulated air-traffic control vigilance task. The results demonstrated the potential of a multi-phase approach to diagnosis of the operator's functional status and fitness to perform tasks requiring sustained attention. Subjective and physiological measures, including TCD indices, derived from the short task battery were predicative of performance on the subsequent vigilance task. The second study demonstrated that the decline in cerebral blood flow over time that accompanies the temporal decline in performance efficiency noted in visual vigilance tasks also appears with an auditory task. This result verifies the utility of TCD in monitoring performance on auditory as well as visual sustained attention tasks, an outcome that has theoretical relevance for an understanding of the mechanisms that control vigilance performance in different sensory modalities and practical relevance for the use of TSD in auditory as well as in visual military tasks requiring sustained attention. A third study is currently in progress at the University of Cincinnati examining whether the physiological and psychological indices used in Study 1 are also predictive of performance on a cognitive vigilance task, imposing high demands on working memory.

Research in progress at Georgia Sate University has developed a simulated sentry task called "Watchkeeper." Work with that task has verified the utility of using TSD to assess current functional efficiency on sustained attention tasks and to predict future performance on those tasks. In addition, the ongoing research at Georgia Sate has indicated that cerebral blood flow and eye movements are associated with different, potentially complementary measures of inattention.

BODY OF REPORT

Work Completed at the University of Cincinnati

UC- STUDY 1: DIAGNOSTIC PREDICTORS OF SENSORY VIGILANCE

A full account of the background to this study may be found in our previous report (Matthews, Warm & Washburn, 2004). This earlier report presented preliminary findings from an initial sample of 97 participants. The study has now been concluded, with a total sample size of 187. In order to avoid undue duplication of material, this report aims to complement the earlier one. Thus, the introduction, method and some elements of the results will be only briefly reported; the reader is referred to Matthews et al. (2004) for further details.

In brief, the study aimed to use indices of physiological and subjective state to predict performance on a sustained attention task. It sought to provide comparative data on the validity of psychophysiological indices of self-report state, salivary cortisol and cerebral blood flow (CBF), measured by transcranial Doppler sonography (TCD), as indicators of performance and functional efficiency. The study focused especially on the predictive utility of the psychophysiological indices. It employed a multi-phase design, in which participants performed a short battery of high-workload tasks, followed by a longer vigilance task requiring sustained attention. It aimed to test whether subjective and physiological responses to the short battery predicted subsequent vigilance performance, using multiple indicator variables as predictors.

Studies at the University of Cincinnati (e.g., Hitchcock et al., 2002; Tripp & Warm, in press) have shown that decreases in blood flow in the cerebral arteries, measured using transcranial Doppler sonography (TCD), are linked to loss of sustained attention. TCD may provide a non-invasive index of cerebral functional status that is promising for efforts to predict performance in stressful environments, within the framework of a resource-workload model of sustained performance (See, Howe, Warm, & Dember 1995). However, work using TCD has primarily explored how task parameters may control both physiological and behavioral response. Individual differences in blood flow have been largely neglected, so that one aim for the present research was to investigate their reliability and validity. In particular, it is unclear whether blood flow responses to different tasks are independent of one another, or whether individuals differ in some more global response that generalizes across tasks. It is also unclear whether there are cross-hemispheric correlations, or whether the two hemispheres are dissociated. On the basis that blood flow may reflect some general resource utilization process, it was hypothesized that individual differences will show some consistency across tasks and hemispheres.

It is also unclear whether TCD can be used to predict loss of performance *in advance of* performance. Short, high workload tasks typically elicit phasic increases in blood flow that are lateralized according to the processing demands of the task (Strabant & Vingerhoets, 2000; Tripp & Warm, in press). These responses may be linked to mobilization of attentional resources and task-directed effort elicited by the performance challenge. To the extent that a larger-magnitude blood flow response signals greater availability of resources and/or effort, it can be hypothesized that the phasic increase in blood flow to short tasks will predict higher levels of blood flow and superior performance on a subsequent, longer vigilance task, expected to elicit decline in blood flow.

It is unclear how blood flow response may align with other subjective and physiological indices that may be linked to the energetics of performance. The study also included measures of salivary cortisol, which may index the activation of a hypothalamic-pituitary-adrenal axis (HPA), corresponding to the well-known ‘fight-or-flight’ response (e.g., Dickerson & Kemeny, 2004). Studies provide conflicting data on how cortisol may relate to performance efficiency, but the measure was included here to test the overlap between blood flow and a widely-used physiological index.

Previous work at UC has established that subjective states may predict performance of vigilance tasks (Matthews & Davies, 1998; Matthews et al., 2001). Our state model discriminates three broad state factors: task engagement (e.g., energy, motivation, alertness), distress (negative affects and low confidence), and worry (self-relevant, intrusive thoughts). Previous studies (e.g., Hitchcock et al., 2003) show that workload parameters of vigilance tasks appear to exert similar effects on both task engagement and blood flow. On this basis, it was hypothesized that task engagement would correlate positively with blood flow. Furthermore, task engagement is a fairly reliable predictor of greater perceptual sensitivity across a range of vigilance tasks, and other attentionally demanding tasks (Matthews & Davies, 1998). Thus, it was predicted that task engagement would predict superior vigilance performance. The study also aimed to test whether task engagement and blood flow predict the same variance in performance, or whether they function as independent predictors. Recent stress research at UC (e.g., Szalma et al., 2004) has highlighted the role of coping in vigilance, i.e., the person’s choice of strategies for dealing with the monotony and stress of the task. To complement the investigation of subjective states, we also included a coping inventory that assesses task-focused, emotion-focused and avoidance coping. The former strategy was expected to be more effective than the two latter ones in the performance setting.

Method

Salient features of the method are summarized here: further details may be found in Matthews et al. (2004).

Participants

There were 187 participants, recruited from UC introductory psychology students, of whom 61% were female. Mean age was 20.0. Inclusion and exclusion criteria are listed in Matthews et al. (2004).

Psychophysiological indices

A Nicolet Companion III TCD unit, with two transducers fitted within a head bracket, was used to record blood flow bilaterally. Saliva was assayed using by having participants chew on a cotton wool ‘Salivette’, that was sent to an external laboratory for analysis.

Questionnaire measures.

The Dundee Stress State Questionnaire (DSSQ: Matthews et al., 1999, 2002) assesses participants' immediate moods, motivations, cognitions and coping strategies, prior to or following task performance. It may be scored for three broad subjective state factors; task engagement, distress and worry. The post-task version also includes a short workload assessment, based on the NASA-TLX (Hart & Staveland, 1988). The Coping Inventory for Stressful Situations (CITS: Matthews & Campbell, 1988) assesses task-focused, emotion-focused and avoidance coping, in the specific context of task performance. Two additional questionnaires used to measure personality and situation awareness, respectively, are not discussed here because they failed to predict relevant criteria: see Matthews et al. (2004) for further details.

Procedure

The sequence of assessments and tasks was as follows:

Time	*Assessment*
0-5	Personality assessment
5-20 mins	Baseline indices: DSSQ (assessment of subjective state) and saliva sample (stored and later assayed for cortisol)
20-25 mins	Baseline measurement of blood flow, recorded bilaterally over the middle cerebral arteries, while the participant views a blank screen with no performance imperative. (This phase was of longer duration for some participants due to extra time taken to obtain a strong TCD signal).
25-35 mins	A short battery of three demanding tasks, each lasting 2 minutes, was performed, with a 2-minute interval before each task. The tasks were a line length detection task ('lines' task), working memory, and psychomotor tracking. CBF is recorded bilaterally during performance.
35-50 mins	Post-task DSSQ and CITS, and a saliva sample.
50-55 mins	Practice of vigilance task
55-95 mins	Performance of a sensory vigilance task, requiring attention to a display resembling air traffic control. CBF is recorded bilaterally during performance.
95-110 mins	Post-task DSSQ, CITS Situation Awareness Technique, and a saliva sample
110-115 mins	Debriefing

Results and Discussion

Results are divided into three sections: (1) manipulation checks, (2) reliability and validity of individual differences in blood flow, and (3) predictors of performance

Manipulation Checks

Subjective state response. Figure 1 represents standardized change scores, compared to baseline, for the three DSSQ secondary factors, following the short battery (left panel) and following vigilance (right panel). The data confirm that the task stressors induced subjective responses as expected. The short battery elevated distress without affecting engagement, whereas the longer vigilance task produced a large-magnitude decline in engagement, accompanied by increased distress.

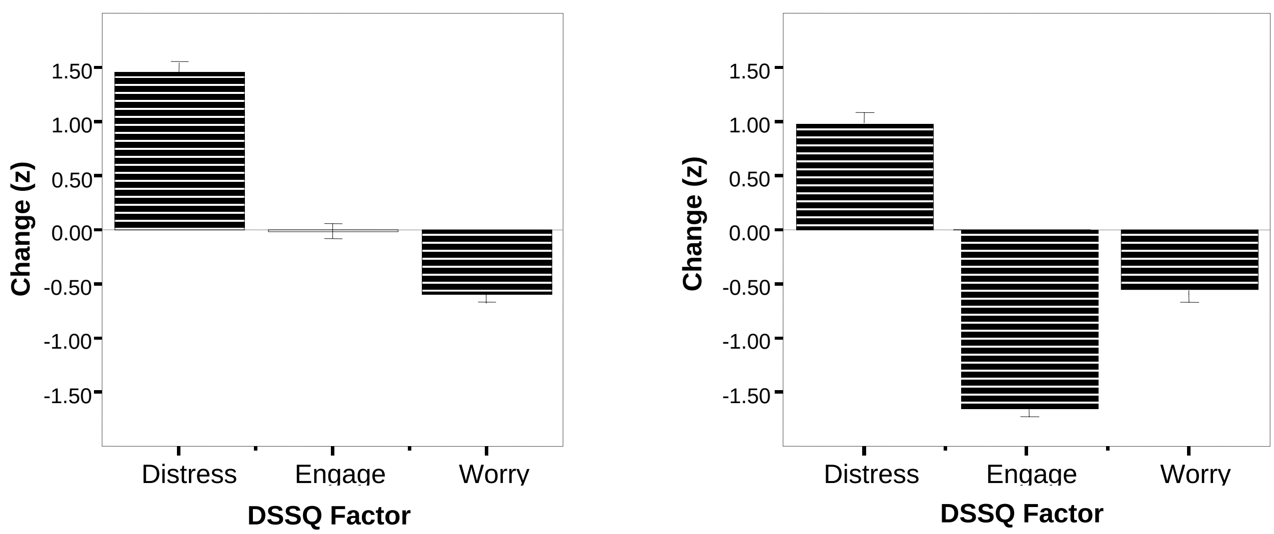


Figure 1. Task-induced change in three DSSQ factors following performance of short task battery (left panel) and vigilance (right panel). Engage. = Task Engagement. Error bars in this and subsequent figures are standard errors.

Workload. Figure 2 shows workload ratings on the six scales of the modified NASA-TLX (0-10 scales). Ratings for the short battery (left panel) confirm that the tasks were rated as demanding in every respect except physical demands, with the highest ratings assigned to mental and temporal demands. Ratings for the vigilance task (right panel) were also high, and are similar to those seen for other demanding vigilance tasks, with mental demands, effort and frustration rated as the major contributors to workload.

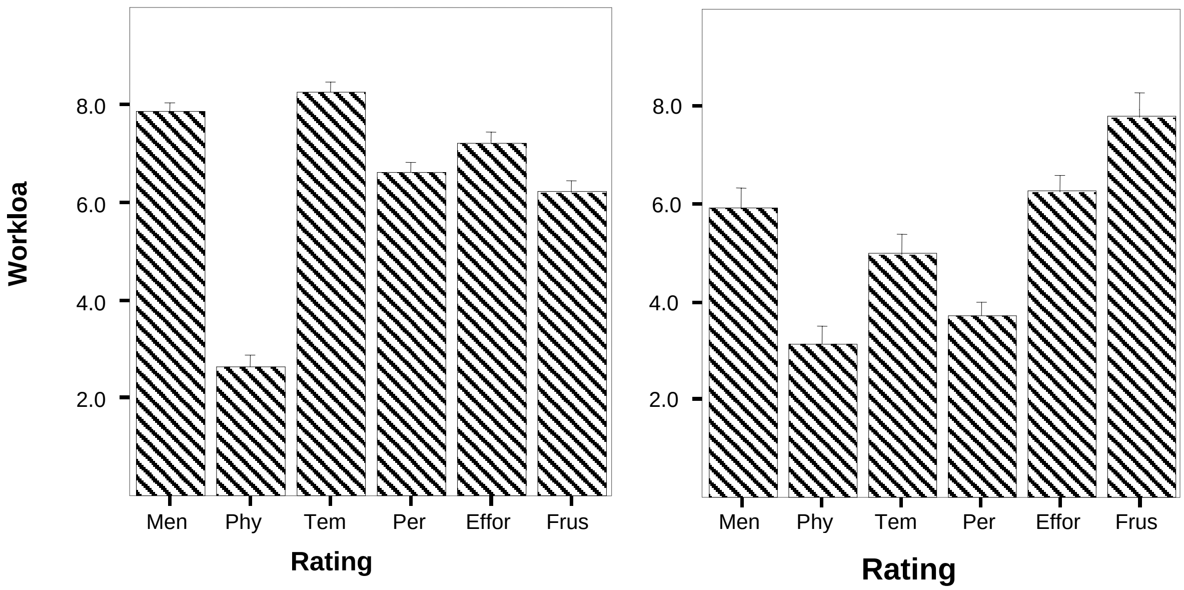


Figure 2. Workload ratings for short battery of tasks (left panel) and vigilance (right panel). Scales are Mental Demand (Ment), Physical Demand (Phys), Temporal Demand (Temp), Performance (Perf), Effort and Frustration (Frust).

Vigilance performance data. Vigilance performance data were calculated for four successive 10-min periods. One-way ANOVAs, with task period as a within-subjects factor (4 levels), were performed to test for temporal change in (1) detection rate, and (2) false alarm rate. Box's epsilon was used when appropriate in calculating degrees of freedom for repeated measures factors to correct for violations of the sphericity assumption (Maxwell & Delaney, 2004). There were significant effects of task period on both detections ($F(3,519) = 31.43$, $p<.001$) and false alarms ($F(3,519) = 4.46$, $p<.05$), as shown in Figure 3. As expected, a vigilance decrement consistent with a loss of perceptual sensitivity over time was obtained.

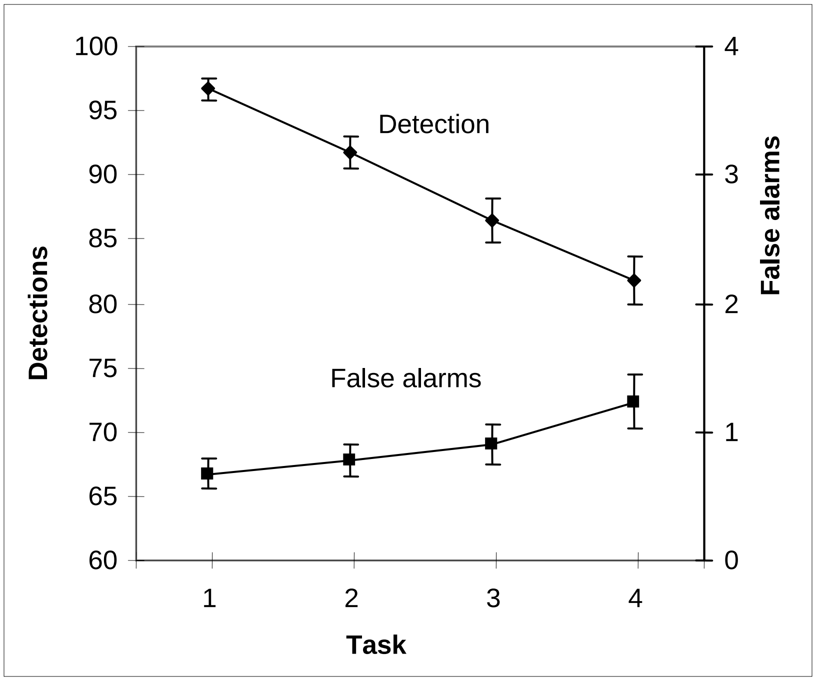


Figure 3. Correct detection (%) and false alarm responses (%) as a function of four 10-minute task period.

Individual differences in blood flow

In this section, we summarize analyses intended to test the reliability and validity of the different blood flow indices taken during the experiment (i.e., baseline, phasic response to short tasks, blood flow during vigilance). *N*s for these analyses vary, primarily because in some participants the TCD signal was lost during recording, on one or both sides, due to the length of the study.

Reliability of measurement. The procedures used for measuring magnitude of the phasic response to performing the short task battery are described and justified in our Year 1 Report (Matthews, Warm, & Washburn, 2004). In brief, the response magnitude for each task was calculated as the percentage change in mean blood flow, relative to the initial baseline assessment of blood flow, prior to performance of any tasks. Left- and right-hemisphere indices were calculated separately.

Table 1 shows the correlations between these phasic response indices. The tendency for the measures to correlate positively demonstrates a generalized response to high workload that varies across individuals. Internal consistency of this response, as indicated by coefficient alpha, may be calculated as 0.74 (left-hemisphere; 3 observations); 0.81 (right-hemisphere; 3 observations); 0.81 (both hemispheres; 6 observations). The Table also shows that left- and right-hemisphere indices for the same task are substantially correlated, indicating that individual differences generalize across the two hemispheres.

A principal components analysis suggested that two separate components could be extracted, correlated at 0.40. Together, they explained 72% of the variance. The first component

was defined by the three right hemisphere indices (range of loadings from pattern matrix: .78 - .93). The second component was defined by the three left hemisphere indices (range of loadings from pattern matrix: .52 - .95). Thus, it may be reasonable to assess left- and right-hemisphere response separately, though bearing in mind that the two responses are positively correlated.

To check the reliability of blood flow measured during vigilance, mean blood flow, as a proportion of baseline, was calculated for each of four successive 10-min periods of task performance. The ranges of correlations within the hemispheres were 0.77 – 0.91 (left) and 0.79-0.93 (right), indicating that individual differences in blood flow were highly consistent. Furthermore, cross-hemisphere correlations at each period were smaller, but also substantial (0.35 – 0.46), suggesting some degree of generalization of individual differences. Coefficient alpha for the four left and four right measures was 0.96, in each case, indicating highly consistent individual differences in response to the vigilance task.

Table 1. Intercorrelations of phasic blood flow indices, for each hemisphere. Tasks: Lines = line length discrimination, WM = working memory, Track = tracking, -P = phasic response index.

			Left Hemisphere			Right Hemisphere		
			Lines-P	WM-P	Track-P	Lines-P	WM-P	Track-P
Left Hemisphere	Lines-P	*r*	-					
		N						
	WM-P	*r*	.523**	-				
		N	172					
	Tracking-P	*r*	.637**	.384**	-			
		N	172	172				
Right Hemisphere	Lines-P	r	.490 **	.306**	.256**	-		
		N	149	150	149			
	WM-P	r	.244**	.547**	.115	.538**	-	
		N	149	150	149	153		
	Tracking-P	r	.374**	.341**	.389**	.668**	.549**	-
		N	149	150	149	154	152	

Note. * $p < .05$, ** $p < .01$

A principal components analysis suggested that two separate components could be extracted, correlated at 0.44. Together, they explained 80% of the variance. The first component was defined by the four right hemisphere indices (range of loadings from pattern matrix: .95 - .99). The second component was defined by the four left hemisphere indices (range of loadings from pattern matrix: .90 - .96). As with the data from the short-task battery, two separate but correlated factors corresponding to the two hemispheres appear to capture blood flow variation.

Table 2. Correlations between (1) baseline and phasic blood flow indices and (2) mean blood flow during periods 1 and 4 of vigilance performance. Left-P, Right-P = mean phasic blood flow response in left and right hemispheres. -1 = period 1, -4= period 4.

		Left Hemisphere		Right Hemisphere	
		Vigilance-1	Vigilance-4	Vigilance-1	Vigilance-4
Left baseline	*r*	-.094	.004	-.046	.053
	N	168	164	132	125
Right baseline	*r*	-.055	.045	-.111	-.058
	N	153	149	137	129
Left-P	*R*	.546**	.470**	.308**	.220*
	N	168	167	132	125
Right-P	*r*	.364**	.281**	.749**	.503**
	N	143	142	137	129

Note. * $p < .05$, ** $p < .01$

Temporal consistency of blood flow. Table 2 shows how the initial baseline measures, and the phasic response indices derived from the short battery, predict blood flow during the first and last periods of vigilance performance (expressed as a percentage change from initial baseline). Baseline blood flow was unrelated to the change in blood flow elicited by performance of the vigilance task. By contrast, the phasic measures were substantially predictive of the blood flow response to vigilance. The ipsilateral correlations were higher than the contralateral ones, although the latter remained significant. Further analyses (see also Matthews et al., 2004) showed that prediction was non-specific with respect to task demands. For example, the phasic responses to working memory and tracking tasks appeared to predict blood flow during vigilance as well as the phasic response to the line length task did, even though the latter short task provided a better match to the information-processing demands of the vigilance task.

Validity of blood flow measurement. Previous work suggests two tests for validity. First (see Stroobant & Vingerhoets, 2000), the magnitude of phasic response should be lateralized, depending on the information-processing demands of the tasks. Specifically, working memory, as a task requiring symbolic processing of verbal and numerical material, should show a larger left- than right-hemisphere response. By contrast, the nonverbal tracking and line length tasks should show a stronger right-hemisphere response. Second, blood flow during performance of the longer vigilance task should show temporal decline, as in previous studies using similar tasks (e.g., Hitchcock et al., 2002).

Effects of task type and hemisphere on phasic blood flow response. Figure 4 shows the effects of blood flow and hemisphere on the task-induced phasic response. A 3 x 2 (task x hemisphere) ANOVA, with repeated measures on both factors, demonstrated that the main effect of task was significant ($F(2,288) = 17.91$, $p<.001$), as was the task x hemisphere interaction ($F(2,134) = 29.93$, $p<.001$). As expected, the line length and tracking tasks produced strong right hemisphere responses, although, unexpectedly, tracking also elicited a large left hemisphere response. By contrast, the working memory condition showed left lateralization.

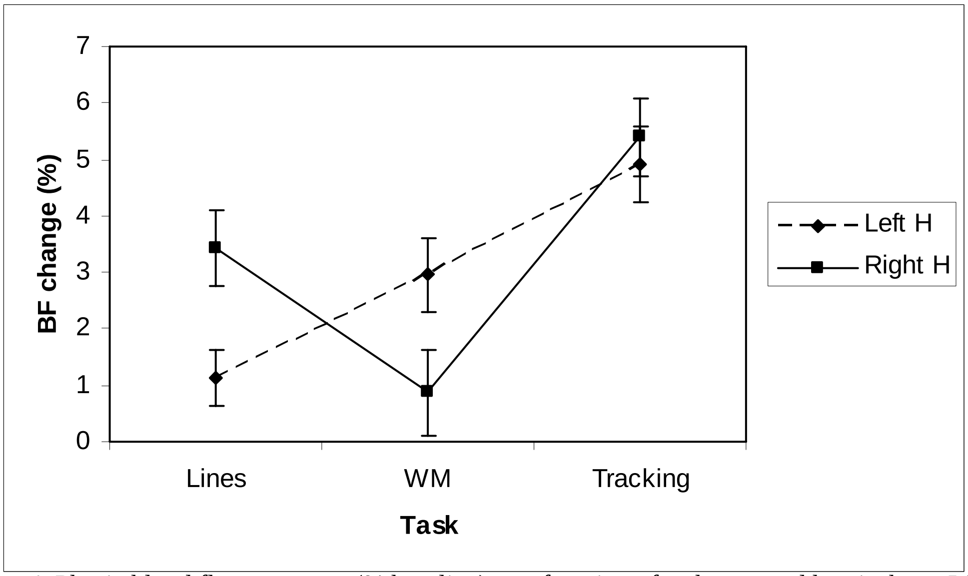


Figure 4. Phasic blood flow response (% baseline) as a function of task type and hemisphere. Lines = line length discrimination, WM = working memory.

Effects of task period on blood flow during vigilance. Figure 5 shows blood flow as a function of 10-minute task period and hemisphere. A 2 x 4 (hemisphere x period) repeated measures ANOVA showed a main effect of period (F(3,360) = 11.93, p<.001), together with a main effect of hemisphere (F(1,120) = 11.93, p<.01). Blood flow declined over time, and was generally higher in the left hemisphere. The trend towards greater rate of decline in the right hemisphere was non-significant.

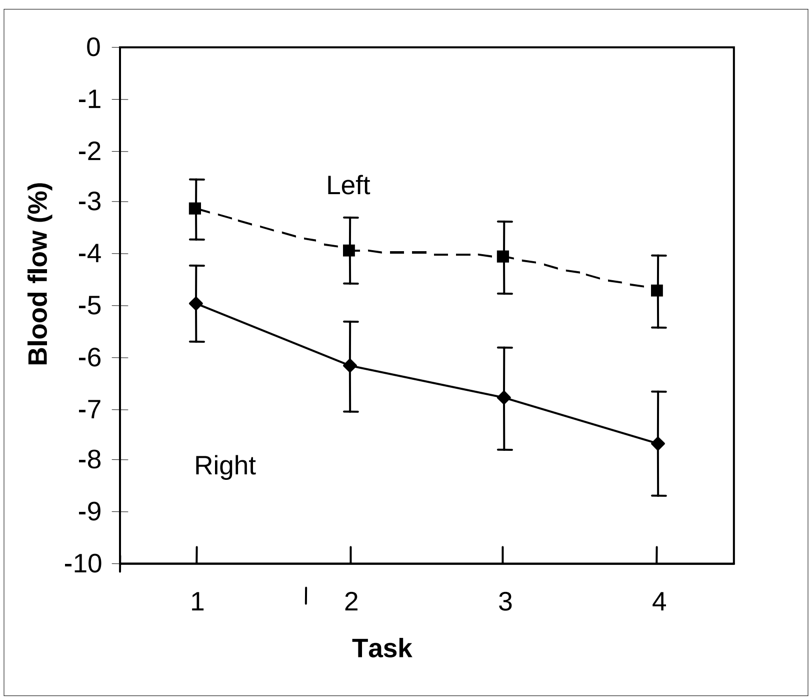


Figure 5. Blood flow (% baseline) during task performance as a function of 10-minute task period and hemisphere.

Predictors of vigilance performance

Correlations between subjective measures and blood flow. Correlations were computed between the three secondary DSSQ factors (task engagement, distress and worry) and the left- and right-hemisphere phasic blood flow indices. Three sets of correlations were available: for subjective state measured at baseline, following the short battery, and following vigilance. It was found that distress and worry were generally unrelated to blood flow, although there was a small but significant negative correlation between distress at baseline and right-hemisphere response ($r = -.164$, $p<.05$). By contrast, there was a consistent tendency for task engagement to correlate with blood flow, as shown in Table 3. Task engagement assessed at baseline and following the short battery predicted right-hemisphere blood flow, whereas left-hemisphere blood flow correlated with engagement post-vigilance.

The blood flow indices were also correlated with the three coping scales assessed by the CITS (task-focus, emotion-focus and avoidance), assessed on two occasions. Task-focused coping was consistently associated with higher right-hemisphere blood flow, and with higher left-hemisphere blood flow following vigilance. Neither the DSSQ nor the CITS variables were associated with initial baseline blood flow, so these findings link subjective state to the task-induced response.

Table 3. Correlations between two subjective factors, assessed on three occasions, with phasic blood flow response measures. Left-P, Right-P = mean phasic blood flow response in left and right hemispheres.

Assessment		Task Engagement		Task-focused coping	
		Left-P	Right-P	Left-P	Right-P
Baseline	*r*	.112	.255**	-	-
	N	172	152		
Post-task	*r*	.172	.256**	.133	.223**
(short battery)	N	172	152	172	152
Post-task	*r*	.207**	.151	.225**	.255**
(vigilance)	N	172	152	172	152

Note. * $p < .05$, ** $p < .01$

We also examined correlations between the DSSQ factors and blood flow during vigilance (mean bloodflow for each 10-minute period). Significant correlations did not exceed chance levels. Individual differences in subjective state appear to relate more to elevations of blood flow, as seen on the short tasks, than to declining blood flow levels, as seen during vigilance.

Correlations between subjective measures and performance. Detection rates on the vigilance task were correlated with subjective state, as assessed by the DSSQ following the short battery and following the vigilance task (see Table 4. Correlations are given for the first and last periods of the task. The first row of correlations here indicates the utility of the DSSQ as a

predictor of *future* sustained performance. The second row of correlations is cross-sectional, but may provide further insights into the stress factors contributing to individual differences in performance. The table shows that task engagement is the only reliable predictor of future performance; those individuals who were most engaged during the short task battery detected more targets on the vigilance task. However, in the cross-sectional correlations, distress appeared to be the most robust predictor. In addition, the baseline measures from the DSSQ were found to be only weakly predictive of vigilance, suggesting that administering the DSSQ following a performance task may be required for predictive validity.

Table 4. Correlations between DSSQ factors and detection rates during four 10-minute task periods (N=174).

Assessment		Task Engagement		Distress		Worry	
		Period 1	Period 4	Period 1	Period 4	Period 1	Period 4
Post-task (short battery)	*r*	.212**	.293**	-.034	-.139	-.049	.042
Post-task (vigilance)	*r*	.027	.186*	-.149*	-.239**	.010	.184*

Note. * $p < .05$, ** $p < .01$

A similar set of correlations was computed to test the relationships between coping strategies, as measured by the CITS, and vigilance performance, as shown in Table 5. High task-focused coping and low avoidance coping were both predictive of a higher rate of detections. The cross-sectional correlations suggest that coping may assume increasing importance during the course of the vigil; period 4 correlations were stronger than those obtained at period 1.

The DSSQ and CITS were also correlated with rates of false alarms on the vigilance task. This performance index proved harder to predict from the subjective measures. However, false alarms in period 1 were significantly correlated with task engagement (r = -0.21, p<.05), task-focus (r = -0.18, p<.05), and avoidance (r = -0.23, p<.01), measured following the short task battery, and with emotion-focus (r = -0.16, p<.05), measured following vigilance.

Table 5. Correlations between post-vigil CITS (coping) scales and detection rates during four 10-minute task periods (N=174).

Assessment		Task-Focus		Emotion-Focus		Avoidance	
		Period 1	Period 4	Period 1	Period 4	Period 1	Period 4
Post-task (short battery)	*r*	.167*	.182*	.022	.182	-.154*	-.162*
Post-task (vigilance)	*r*	.155*	.346**	-.078	-.069	-.040	-.251**

Note. * $p < .05$, ** $p < .01$

Table 6. Correlations between phasic blood flow indices and two indices of vigilance performance during the first and fourth task periods .

	Detections		False Alarms	
	Period 1	Period 4	Period 1	Period 4

Left Hemisphere	Lines-P	*r*	-.039	.188*	-.154*	-.030
		N	160	160	160	160
	WM-P	*r*	-.144	.093	-.124	-.050
		N	160	160	160	160
	Tracking-P	*r*	.035	.212**	-.124	-.050
		N	160	160	160	160
	Left-P	r	-.055	.202**	-.121	.002
		N	160	160	160	160
Right Hemisphere	Lines-P	r	.050	.053	-.064	-.122
		N	144	144	144	144
	WM-P	r	.020	.193*	-.133	-.181*
		N	144	144	144	144
	Tracking-P	r	.229**	.146	-.202*	-.133
		N	143	143	143	143
	Right-P	r	.074	.161	-.185*	-.176*
		N	140	140	140	140

Note. * $p < .05$, ** $p < .01$

Correlations between blood flow and performance. Table 6 gives correlations between the phasic blood flow measures and vigilance performance, indexed separately as correct detections and false alarms, at periods 1 and 4. In general, higher blood flow response to the short tasks to predicted a higher rate of detections and a lower rate of false alarm responses, as expected. There appears to be no task-specificity of prediction from the blood flow measures. In particular, bloodflow response to the lines task was, in general, no more strongly related to subsequent vigilance performance, than blood flow response to working memory and tracking tasks. Left hemisphere response may be more predictive of correct detections, and right hemisphere response to predict false alarms, especially in period 4, but it is unclear how robust this difference is. For example, the correlation of 0.161 between mean right hemisphere response and correct detections just fails to attain significance ($p = .057$). In general, though, blood flow predicted vigilance as expected, although correlation magnitudes were modest. Blood flow measured during vigilance itself correlated with performance only at chance levels; the phasic measure appears to be more diagnostic.

Cortisol and performance. Superficially, the data suggest that exposure to high workload tasks *lowers* salivary cortisol levels, relative to initial baseline. Means (and SDs) for baseline and the two post-task assessments were, in temporal order, .32 (.26), .21 (.14) and .24 (.21) µg/dL. However, each cortisol measurement was substantially negatively correlated with time of day, reflecting the circadian rhythm in cortisol, and rendering interpretation of baseline cortisol assays questionable. To obtain an index of cortisol response to the stressors, the measures taken following (1) the short task battery, and (2) the vigilance task, were separately residualized against baseline. A positive residual indicates that the observer showed a more positive cortisol response to the task than would be expected on the basis of baseline cortisol. The two residual measures proved to be independent of time of day.

Cortisol was only weakly correlated with the subjective variables. Baseline cortisol was correlated with worry following the short task battery ($r = .15$, $p < .05$), and following the

vigilance task (r = .19, p < .05). This measure also related to emotion-focused coping post-vigilance (r = .18, p < .05). The cortisol response to the short task battery (measured by the residual) was correlated with baseline task engagement (r = .20, p < .01), and with post-vigilance engagement (r = .17, p < .05). The cortisol response to the vigilance task was associated with higher emotion-focused coping post-vigilance (r = .18, p < .05). 6 out of 45 correlations reached significance, and so the incidence of significance here is not far above chance levels.

A weak trend towards positive correlations between the cortisol response indices and blood flow was also apparent. The cortisol response to the short task battery was positively correlated with left-hemisphere blood flow response to the battery (r = .16, p < .05), and with left-hemisphere blood flow during the first period of the vigilance task(r = .18, p < .05). Cortisol response to the vigilance task correlated with both left- and right-hemisphere blood flow during the first period of vigilance (rs = .20, .18, ps < .05), and with left-hemisphere blood flow during period four of the vigilance task(r = .17, p < .05).

Performance correlates of the residualized cortisol response measures are given in Table 7. These measures were predictive only of period 4 performance, at which time period, higher cortisol response tended to relate to higher rates of both correct detections and false alarms, implying that cortisol may relate to adoption of a lower response criterion.

Table 7. Correlations between residualized cortisol responses assessed following task performance, and two indices of vigilance performance during the first and fourth task periods (N=168).

Assessment	Detections		False Alarms	
	Period 1	Period 4	Period 1	Period 4
Post-task (short battery)	-.102	. 159*	-.057	.154*
Post-task (vigilance)	-.010	-.007	.064	.243**

Note. * p < .05, ** p < .01

Workload as a moderator factor. The data just reported show correlations between blood f low and correct detection rates in the expected direction, but they were of fairly modest size. One possibility is that the functional significance of blood flow depends on other, moderator factors. A prime candidate for a moderator factor is the workload of the task. The data show considerable individual differences in workload. Mean workload on the modified NASA-TLX used in this study was 5.08, close to the midpoint of the 0-10 scale. The SD was 1.53, with individual scores ranging from 0-9.0, indicating substantial variability in perceptions of task demands. The information-processing constraints on task performance may be rather different, depending on whether the task is perceived as undemanding, or imposing a high processing load.

Ungar et al. (2005) have recently suggested that, depending on task demands, processing may be limited by two rather different factors. At low workloads, attentional resources are likely to be sufficient, and so performance may depend on the voluntary effort applied to the task, i.e., the extent to which the person chooses to deploy the resources available. At high workloads, task demands are more likely to exceed resources, and so performance may be more sensitive to variation in resources than variation in effort.

Thus, it may be that the diagnosticity of blood flow as a predictor of performance may vary with workload. If, as often supposed (e.g., Hitchcock et al., 2003, Tripp & Warm, in press), blood flow indexes resources, then the predictive validity of blood flow should increase with task demands. By contrast, if blood flow relates to effort rather than to resources, then blood flow should predict performance more strongly when workload is low.

As a first test of whether workload operates as a moderator of the blood flow – performance correlation, the sample was divided at the median (5.1) on the NASA-TLX score assigned to the vigilance task, and correlations between blood flow indices and performance calculated separately for the two median-split groups (high and low workload). Table 8 shows that blood flow was only significantly correlated with a higher rate of correct detections in those subjects who rated workload as low.

These data are suggestive of a moderator effect for workload, with – contrary to a resource theory argument – blood flow appearing to be more predictive of correct detections when workload was perceived as low. Ungar et al.'s (2005) analysis would suggest that blood flow may relate to deployment of effort, which limits performance when resources are plentiful. However, the use of a median-split is a crude analytic technique. A more sophisticated test of the moderator hypothesis is to test the interaction between workload and blood flow, which is done using a regression model in the section that follows.

Table 8. Correlations between phasic blood flow measures and detection rates during four 10-minute task periods, in participants reporting low and high task workload. Left-P, Right-P = mean phasic blood flow response in left and right hemispheres.

Hemisphere		Detections-1	Detections-2	Detections-3	Detections-4
Low workload					
Left	*r*	.041	.185	.293**	.271*
	N	78	78	78	78
Right	*r*	.059	.387**	.235*	.318**
	N	68	68	68	68
High workload					
Left	*r*	-.117	-.031	.024	.128
	N	82	82	82	82
Right	*r*	.117	-.103	-.039	-.053
	N	72	72	72	72

Note. * $p < .05$, ** $p < .01$

Regression models. Thus far, predictors of vigilance performance have been analyzed separately. In this section, we report multiple regression models that examined whether the prediction of performance may be improved through using multiple independent predictors. Regression models were constructed in five steps. First, two control variables – time of day and

gender – were entered to control for these potential sources of variance. Second, the three physiological indices derived from the short task battery were included. These indices comprise the two phasic blood flow response measures, and the residualized cortisol index. Third, the three DSSQ factors were entered. The last two steps tested the moderator role of workload as discussed in the previous section, entering, fourth, overall workload for vigilance, and, fifth, two product terms representing the workload x blood flow interaction. These variables were standardized prior to the calculation of the product terms to reduce collinearity between linear and product terms.

The first regression (see Table 9) used detection rate in period 4 of the vigilance task as the criterion, so as to predict loss of vigilance, evident towards the end of the task. Table 9 shows that both physiological and subjective variables add significantly to the prediction of detection rate. Together (steps 2 and 3), they contribute an addition 12% to the variance explained. The regression equation at step 3 suggests that useful prediction from the short battery indices is possible. At this step, R was 0.43, $F(8,131) = 3.69$, $p < .01$. The individual predictors that attained significance were time of day ($\beta = 0.17$, $p <.05$) and task engagement ($\beta = 0.22$, $p <.01$). Later time of day and high task engagement independently predicted performance.

Adding workload (step 4) failed to add to the variance explained, but the two interaction terms were significant, confirming that the predictive validity of blood flow varies with workload. At step 5, R was 0.48, $F(11,128) = 3.52$, $p < .01$. The individual predictors that attained significance were time of day ($\beta = 0.18$, $p <.05$), task engagement ($\beta = 0.20$, $p <.05$), and workload x right-hemisphere blood flow ($\beta = 0.27$, $p <.01$). The interaction term is not truly predictive, in that workload was measured post-performance, but it points towards a need to accommodate the role of workload as a moderator in the prediction of performance.

Table 9. Summary statistics for the regression of correct detections (period 4) on multiple predictor variables.

Step	Variables	Change in R^2	*F*	df	Sig.
1	Control (Time, gender)	.066	4.87	2,137	$p<.01$
2	Physiological (Left-P, Right-P, Cortisol)	.058	2.98	3,134	$p<.05$
3	DSSQ (Engagement, Distress, Worry)	.059	3.16	3,131	$p<.05$
4	Workload	.000	.00	1,130	NS
5	Interaction terms (Left-P, Right-P x workload)	.048	4.04	2,128	$p<.05$

A similar regression equation was constructed with false alarms in period 4 as the criterion. Summary statistics are given in Table 10. In this instance, the physiological variables, but not the subjective variables predicted performance. Both the linear workload term and the workload x blood flow interaction terms added significantly to the equation. R for the equation at

step 5 was 0.41, $F(11,128) = 2.36$, $p < .05$. Significant predictors in the final equation were the linear workload term ($\beta = 0.27$, $p < .01$), cortisol ($\beta = 0.17$, $p < .05$), the linear right-hemisphere blood flow term ($\beta = -0.26$, $p < .05$), and the workload x right-hemisphere blood flow interaction ($\beta = -0.31$, $p < .01$). By contrast with the regression for correct detections, false positives appear to be best predicted from physiological rather than subjective state variables, although in both equations, blood flow effects were moderated by perceived workload.

Table 10. Summary statistics for the regression of false alarms (period 4) on multiple predictor variables.

Step	Variables	Change in R^2	*F*	Df	Sig.
1	Control (Time, gender)	.011	.80	2,137	NS
2	Physiological (Left-P, Right-P, Cortisol)	.066	3.17	3,134	$p<.05$
3	DSSQ (Engagement, Distress, Worry)	.001	.05	3,131	NS
4	Workload	.029	4.27	1,130	$p<.05$
5	Interaction terms (Left-P, Right-P x workload)	.061	4.73	2,128	$p<.01$

UC-STUDY 2: EFFECTS OF SENSORY MODALITY AND EVENT ASYNCHRONY ON VIGILANCE PERFORMANCE AND CEREBRAL HEMOVELOCITY

Several investigations using positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) procedures have been successful in demonstrating that changes in cerebral blood flow and glucose metabolism are involved in the performance of sustained attention or vigilance tasks (Parasuraman, Warm & See, 1998). These studies identified multiple brain regions that are active during the performance of such tasks, including the nucleus locus coerulus, the brainstem reticular formation, the midbrain tegmentum, the intralaminar region of the thalamus, the cingulate gyrus, and the frontal lobe. However, as Parasuraman et al. (1998) emphasized, an important limitation of these studies is their failure to correlate brain activity with performance efficiency, perhaps due to the high costs and restrictive environments associated with PET and fMRI. Thus, the functional role of the brain systems identified in the imaging studies remains largely unknown.

The high costs and the restrictions of PET and fMRI may be circumvented in studying brain systems in vigilance by employing transcranial Doppler sonography (TCD) – a relatively inexpensive and noninvasive procedure that allows for continuous monitoring of cerebral blood flow (CBF) in the main-stem intracranial arteries. When an area of the brain becomes

metabolically active, as in the performance of mental tasks, by-products of this activity, such as CO_2 increase. This results in an elevation of blood flow to the region to remove the waste product (Aaslid, 1986). Thus, CBF may be viewed as a metabolic index of information processing (Stroobant & Vingerhoets, 2000; Tripp & Warm, in press). Along this line, Warm, Matthews, and their associates have carried out a series of studies featuring CBF measurements in the right and left medial cerebral arteries which carry 80% of the blood flow to the brain (Matthews, Warm, & Washburn, 2004; Warm & Parasuraman, in press). These studies have indicated that the vigilance decrement, the decline in signal detections over time that typifies vigilance performance, is paralleled by a decline in CBF. In addition, the absolute level of blood flow in these studies was directly related to the psychophysical and cognitive demands of the vigilance task, the availability of reliable cues to the imminent appearance of signals to be detected, and to the ability of observers to form accurate expectancies as to the time of signal arrival. All of these overall effects were lateralized to the right cerebral hemisphere, consistent with PET and fMRI studies indicating the operation of a right-hemispheric system in the functional control of vigilance performance.

It is noteworthy that all of the vigilance studies involving TCD were conducted in the visual modality. However, vigilance tasks can also be performed in the auditory modality and the sensory modality of signals is not a matter of indifference where vigilance is concerned. The overall level of performance in auditory tasks is greater than that in visual tasks and the vigilance decrement is less pronounced in the auditory than in the visual modality (see reviews by Ballard, 1996; Davies & Parasuraman, 1982; Warm, 1993; Warm & Jerison, 1984). Accordingly, one goal for the present study was to determine the degree to which the vigilance decrement is accompanied by a decline in CBF in comparable visual and auditory vigilance tasks. There are theoretical and operational reasons for a study of this sort.

On a theoretical level, one might conclude from the sensory differences described above that sustained attention in audition and vision may be based on different central properties, a possibility that would greatly complicate efforts to understand the mechanisms that underlie sustained attention. On the other hand, the presence of substantial intermodal correlations between auditory and visual vigilance tasks (r’s ranging from.65 to .80) along with the findings of successful intermodal transfer in training for vigilance and superior performance with redundant dual-mode audio/visual displays relative to single-mode auditory or visual displays have led Warm and Jerison (1984) to a different conclusion. They affirm that while modality-specific factors are important, within limits, vigilant behavior is a common characteristic of the observer. That view would be supported by a finding that the vigilance decrement is accompanied by a similar blood flow decrement in both tasks occurring in common cerebral arteries. On a more practical level, the finding that the vigilance decrement in visual vigilance tasks is accompanied by a corresponding decline in cerebral blood flow suggests that CBF might serve as a useful way to “monitor the monitor” and to determine when personnel who are performing visual sustained attention tasks in operational settings, such as military surveillance, may be in need of rest or replacement. A similar result with auditory tasks would increase the operational potential for using CBF in this way.

In a critical earlier study, Hatfield and Loeb (1968) raised an important methodological issue in regard to audio-visual comparisons in vigilance. They pointed out that disparities in the types of discriminations involved, the salience of the displays to be observed, and the difficulty

of the discriminations to be made were not equated in previous studies of sensory differences in vigilance and could have contributed to the outcomes of those studies. Accordingly, since the perception of time correlates strongly in the auditory and visual modes under alerted conditions (Loeb, Behar, & Warm, 1966), temporal discriminations were featured in this investigation, and efforts were made to specifically control for disparities in display salience and discrimination difficulty.

There is still another psychophysical factor in vigilance that might be related to CBF – the temporal structure in the flow of background events that house the critical signals for detection. Background events in vigilance can appear in a synchronous, temporally regular manner, e.g., once every 12 sec at a slow event rate of 5events/min or once every 2 sec at a faster event rate of 30 events/min. Under synchronous conditions, observers can align attention with predictions about when an event requiring observation will appear. Therefore, they do not have to attend continuously to the display and can take "task contingent" time outs from observing. In contrast, when the schedule of background events is asynchronous, observers cannot be certain when an event requiring inspection will occur and must attend continuously to the vigilance display. Scerbo and his associates report that an asynchronous event schedule results in a poorer level of signal detections than a synchronous schedule (Scerbo, Warm, & Fisk, 1986; Scerbo, Warm, Doettling, Parasuraman, & Fisk, 1987). To the degree that the asynchronous schedule imposes a greater information-processing demand on observers than the synchronous schedule, it is anticipated that blood flow will be greater in the asynchronous condition. Like the sensory modality of signals, examination of the effects associated with the event schedule also has significance for operational military tasks, particularly for surveillance tasks wherein personnel must monitor the environment for the aperiodic appearance of stimuli that may represent enemy threats, like for example, sentry tasks.

Method

Seventy-two right-handed undergraduates (36 men and 36 women) from introductory psychology classes at the University of Cincinnati served as observers. Twelve observers (6 men and 6 women) were assigned at random to each of 4 experimental conditions defined by the factorial combination of two sensory modalities (auditory and visual) and two event schedules (synchronous and asynchronous). To ensure that time-based changes in blood flow were indeed task-linked, the remaining students served as passive controls that simply looked at or listened to the visual or auditory displays without an information-processing imperative for a time period equal to that of the active vigilance tasks. Six passive observers (equated for sex) were assigned at random to serve in each of the four cells of the 2 × 2 design.

In all active experimental conditions, observers participated in a continuous 40-min vigil divided into four 10-min periods of watch. The auditory and visual displays that were employed were taken from Szalma et al. (2004). Observers monitoring the visual display viewed the repetitive presentation of a horizontally oriented 2 mm x 9 mm white bar (transluminance = 37.8 cd/m^2) that appeared against a gray background (transluminance = 3.51 cd/m^2) on a video display terminal (VDT). Neutral events, requiring no response from the observer, were flashes lasting 247.5 ms. Observers monitoring the auditory display listened to 247.5 ms bursts of white noise presented binaurally via Koss 3.5mm cylindrical earphones inserted into the external

auditory meatus of each ear. Critical signals in the visual case were be brief 125 ms flashes of the light bar. In the auditory case, critical signals were brief 200 ms bursts. The disparity in duration changes used to specify auditory and visual signals was necessary to compensate for greater temporal acuity in the auditory mode under alerted conditions (Szalma, et al., 2004). In all conditions, observers equated the apparent loudness of the noise to the apparent brightness of the visual stimulus by means of a cross-modality matching procedure (Stevens, 1959). The mean auditory intensity of the loudness/brightness matches was 53.34 dB(A). The displays were updated once every 2000 ms in the synchronous event condition. In the asynchronous condition, the schedule of updates varied from 600 ms to 3000 ms with a mean of 2000 ms. In all conditions, 10 critical signals were presented in each watchkeeping period. Observers indicated their detections of critical signals by pressing the spacebar a computer keyboard. Responses occurring within 1.5 sec after the onset of critical signals were recorded automatically as correct detections. All other responses were recorded as errors of commission or false alarms. Hemovelocity measurements in cm/sec were taken bilaterally from the right and the left middle cerebral arteries by means of a DWL/Multi-Dop X4 TCD unit.

Observers were tested individually in a 2.85 x 4.32 x 2.42 m windowless laboratory room. The VDT was located at eye-level on a table sited 60 cm directly in front of the seated observer. Ambient illumination in the testing room was 0.22 cd/m^2. It was provided by a single 11-watt incandescent bulb housed in a portable light fixture and positioned above and behind the seated observer in order to minimize glare on the VDT. Observers were separated from the TCD equipment by a curtain in order to minimize distractions from that equipment. Stimulus presentations and response recording were orchestrated by a Dell personal computer with a Pentium-four processor running Super Lab (version 2.0) software.

Prior to the initiation of the main vigil, observers were acclimated to the TCD recording procedure in a 5-min resting baseline period during which they were asked to relax and breathe normally while gazing at a blank VDT screen. They were then given a 5-min practice session that duplicated the task that they were to perform. Ten critical signals were presented during the practice period. To be retained in the study, observers were required to detect a minimum of 80% of the critical signals and commit no more than 10% false alarms during practice. Observers failing to pass this criterion were given a second 5-min practice session. Only the data of those participants who passed criterion on either the first or second practice session were included in the study. The mean percentages of correct detections during practice exceeded 90% for all experimental conditions. Observers surrendered their wristwatches, pagers, and cell phones upon entering the laboratory and had no knowledge about the length of the vigil other than it would not exceed 75 m.

Results and Discussion

Correct Detections. A 2 (mode) x 2 (event schedule) x 4 (periods) mixed analysis of variance (ANOVA) based upon an arcsine transformation of the percentages of correct detections revealed that performance efficiency declined significantly over time, F (3, 122) = 22.27, p<.001. No significant effects were obtained for the mode and event rate factors and all of the interactions in the analysis lacked significance, p >.05 in each case. In this, and all subsequent ANOVAs, Box's epsilon was employed to correct for violations of the sphericity assumption (Maxwell & Delaney, 2004).

The vigilance decrement is displayed in Figure 6. In this, and all other figures related to Study #2, error bars are standard errors. Tests of trend indicated that the linear component of the function shown in the figure was significant, F (1, 44) = 49.39, p <.001. The cubic and quadratic components were not significant, p >.05.

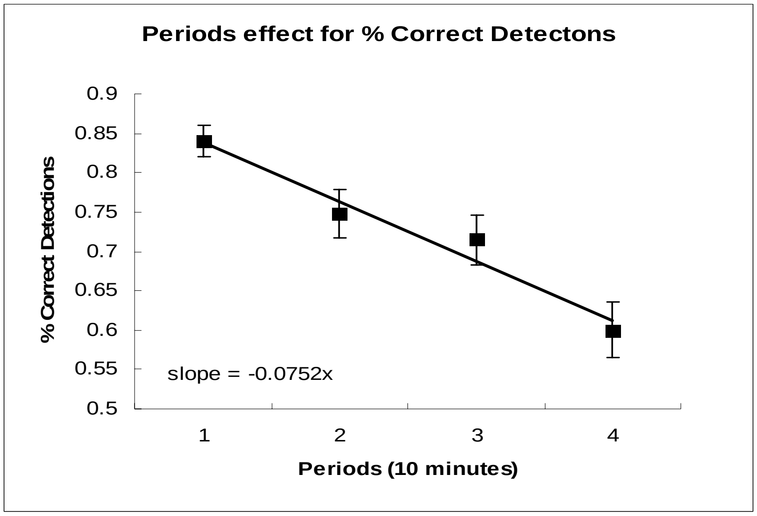


Figure 6. Mean percentage of correct detections as a function of periods of watch.

False Alarms. A similar analysis on an arcsine transformation of the percentages of false alarms revealed that the frequency of errors of commission also declined significantly over time, F (2, 94) = 12.31, p <.001. In addition, there was a significant main effect for event schedule, F (1, 44) = 7.87, p *<.01)* and a significant Mode x Event Schedule interaction, F (1, 44) = 6.64, p <.02. None of the remaining sources of variance in the analysis of the false alarm scores reached significance, p >.05 in all cases.

The temporal decline in false alarms is shown in Figure 7. As was the case with correct detections, a trend analysis revealed that the frequency of errors of commission declined linearly with time on task, F (1, 44) = 23.04, p < .001, and that there were no significant cubic or quadratic components in this relation, p *>.05.*

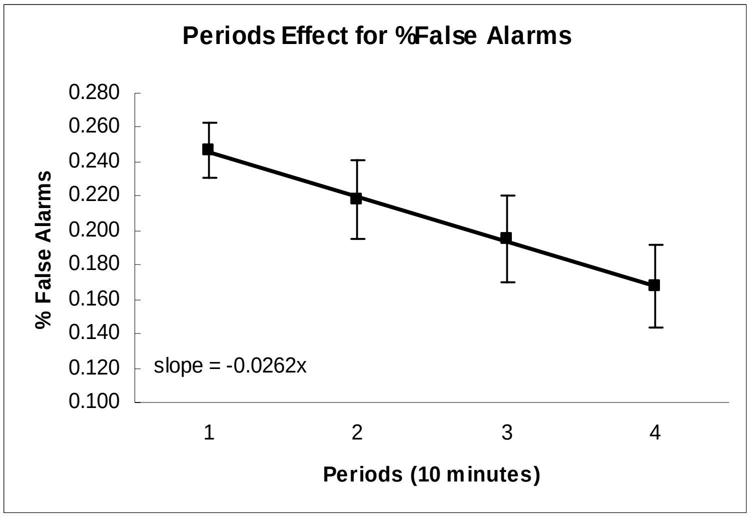


Figure 7. Mean percentage of false alarms as a function of periods of watch.

The significant Mode x Event Schedule interaction in the false alarm data is presented in Figure 8. It is evident in the figure, that false alarms were greater in the asynchronous than in the synchronous condition when observers monitored for visual signals while there was no difference between the event schedules in the auditory condition.

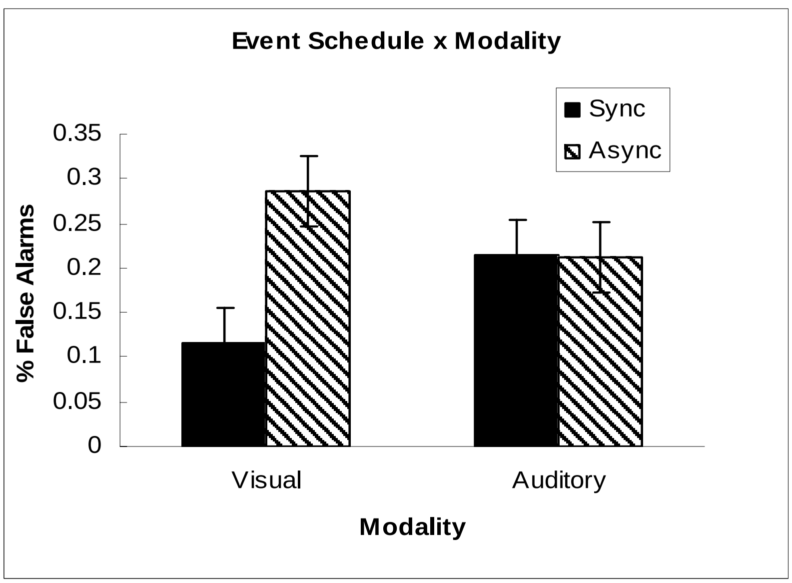


Figure 8. Percent false alarms in the synchronous and asynchronous conditions within each sense modality.

Cerebral Hemovelocity. To take account of the wide range of hemovelocity scores present in the population (Tripp & Warm, in press), the scores for all observers in this study were expressed as a proportion of the last 60-sec of their 5-min resting baseline (Matthews, et al., 2004; Warm & Parasuraman, in press). Inspection of the baseline data indicated that the baseline scores were similar in all experimental groups. Thus, any hemovelocity effects

associated with the sensory modality of signals, the event schedule, and cerebral hemisphere cannot be attributed to sampling artifacts in the initial resting baseline.

A 2 (mode) x 2 (event schedule) x 2 (cerebral hemisphere) x 4 (periods) mixed- ANOVA of the hemovelocity data revealed that like the case with the performance measures, cerebral blood flow also declined significantly over time, $F(2, 92) = 29.0$, $p < .001$, as shown in Figure 10. Once again, tests for trend revealed that the linear component in the relation between the dependent variable of interest and time on task was significant, $F(1, 44) = 45.85$, $p < .001$ while the cubic and quadratic components were not, $p > .05$. In addition to the main effect for periods of watch, the main effect for hemisphere was also significant, $F(1, 44) = 4.86$, $p < .05$. As shown in Figure 10, overall blood flow was greater in the right as compared to the left hemisphere.

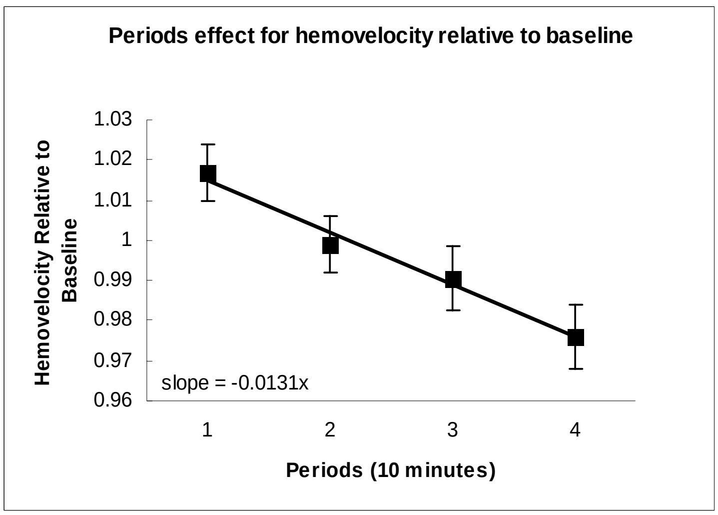


Figure 9. Mean cerebral hemovelocity scores as a function of periods of watch.

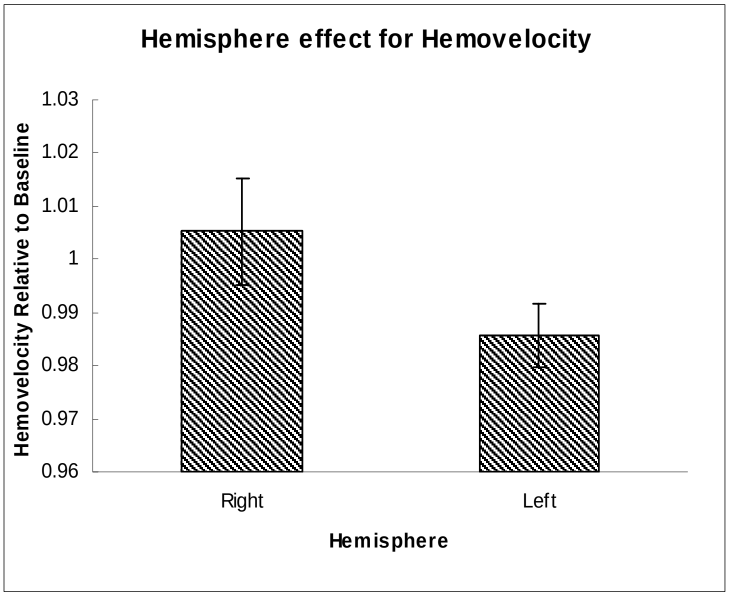


Figure 10. Mean cerebral hemovelocity scores in the right and left cerebral hemispheres.

While the main effect for event schedule was not statistically significant (p >.05), the influence of this variable emerged in several significant interactions. Included were the Schedule x Hemisphere interaction, $F(1, 44) = 5.53$, $p<.05$, and the Schedule x Hemisphere x Periods, $F(2, 103) = 3.61$, $p<.05$, and the Schedule x Mode x Periods, $F(2, 92) = 2.98$, $p<.05$, interactions. All remaining sources of variance in the ANOVA of the blood flow data lacked significance, $p>.05$.

The Event Schedule x Hemisphere x Periods interaction is presented in Figure 12. Hemovelocity scores for the synchronous and asynchronous event schedules are plotted as a function of periods of watch. Data for each hemisphere are presented separately in each panel. Within the right hemisphere, blood flow was clearly greater for the asynchronous than the synchronous condition throughout the vigil. By contrast, in the left hemisphere, blood flow was similar for the two event schedules early in the vigil but declined more rapidly in the asynchronous condition so that by the end of the vigil, blood flow in the synchronous condition exceeded that in the aysyncronous condition.

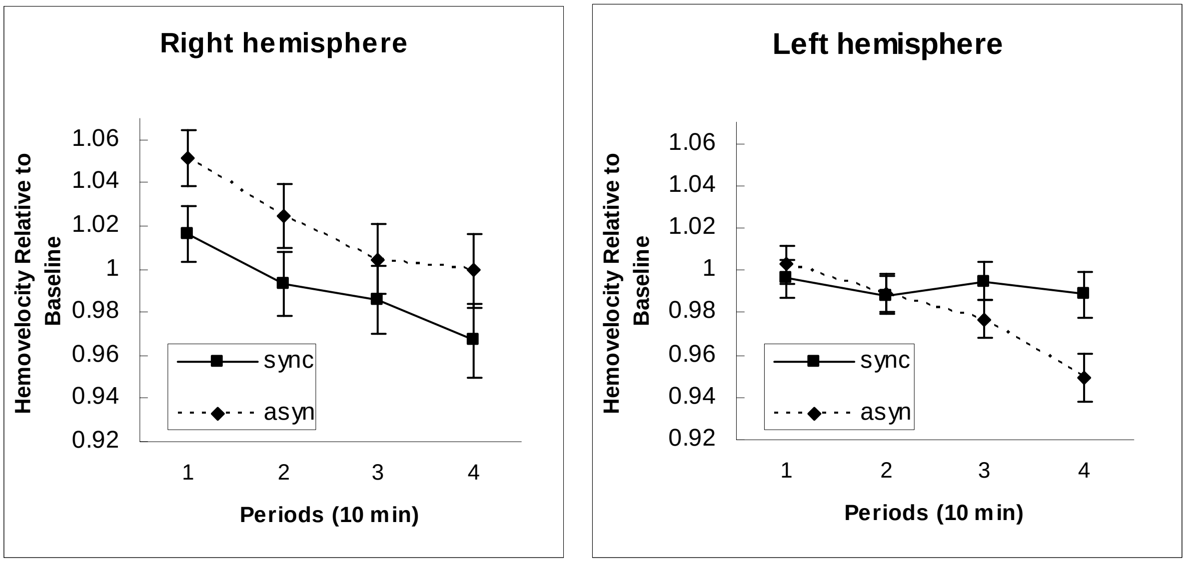


Figure 11. Mean cerebral hemovelocity scores for the synchronous and asynchronous event schedules as a function of periods of watch. Data for the right and left hemispheres are presented separately in each panel.

The Event Schedule x Mode x Periods interaction is shown in Figure 12. Mean blood flow scores for the synchronous and asynchronous conditions are plotted as a function of periods of watch. Data for the visual and auditory modalities are presented separately in each panel. It is evident in the figure that when monitoring for visual signals blood flow was consistently greater in the asynchronous than in the synchronous event condition. When observers monitored for auditory signals, blood flow was also greater in the asynchronous condition early in the watch but it declined more rapidly over time in the asynchronous than in the synchronous condition so that by the end of the vigil, blood flow in the synchronous condition exceeded that of the asynchronous condition.

Control Observers. Data for the control observers who viewed the vigilance display without a work imperative are still being collected. At this point, seven observers have completed the control run. As was the case in the earlier vigilance blood flow studies (Matthews, et al., 2004; Warm & Parasuraman, in press), the scores for these observers have remained stable over time throughout the 40-min session.

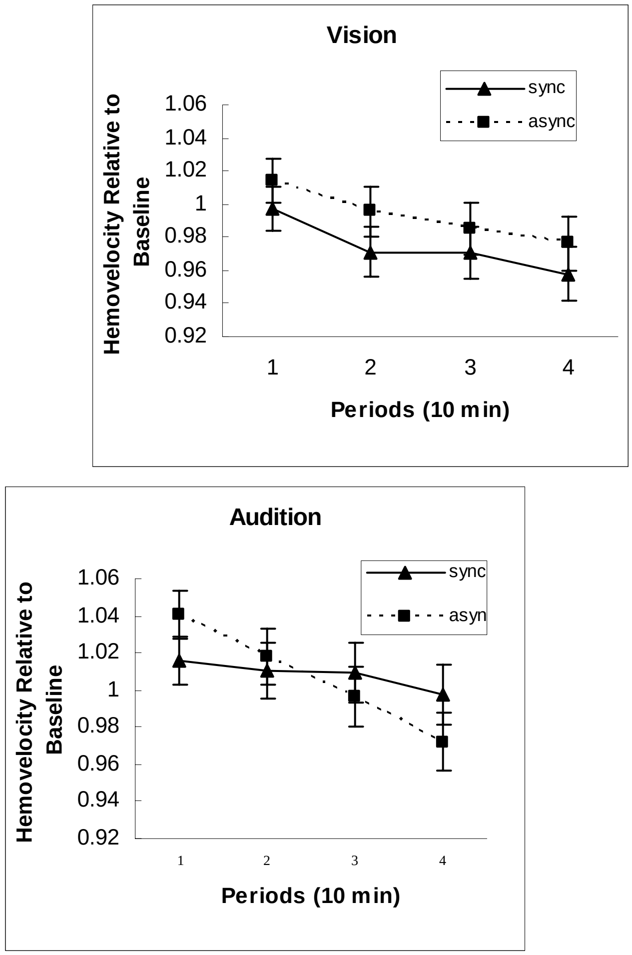


Figure 12. Mean cerebral hemovelocity scores for the synchronous and asynchronous event schedules as a function of periods of watch. Data for visual and auditory conditions are presented separately in each panel.

One goal for the present study was to determine the degree to which the vigilance decrement is accompanied by a decline in cerebral blood flow in auditory and visual tasks under conditions in which possible confounding effects arising from disparities in the type stimulus dimensions being monitored, discrimination difficulty, and display salience were controlled. The results of the study indicated that correct detections and false alarms both declined significantly over time in a linear manner that was independent of the sensory modality of signals. The temporal trends for both performance measures were paralleled by a similar overall linear decline in CBF that also was independent of the sensory modality of signals. Clearly, the task related decline in blood flow over time found in earlier visual vigilance studies (Matthews, et al., 2004; Warm & Parasuraman, in press) is not restricted to the visual modality; it appears with auditory stimuli as well. A result of this sort is consistent with the view and that while stimulus–specific sensory factors are important in vigilance, within limits, vigilant behavior is a general characteristic of the observer (Warm & Jerison, 1984). It is also consistent with the view that the brain engages in a synthesis of similar streams of information carried over different sensory

channels (Calvert, Spence, and Stein, 2004; Walk & Pick, 1981). On a more applied level, the present results suggest that declines in CBF over time may be useful in uncovering a need for rest or replacement among military personnel performing auditory as well as visual monitoring tasks.

A second goal for this study was to test the expectation that CBF would be greater in the context of an asynchronous as compared to a synchronous event schedule. Unlike the case in earlier experiments with the background event factor (Scerbo, Warm, & Fisk, 1986; Scerbo, Warm, Doettling, Parasuraman, & Fisk, 1987), the effects of this variable did not appear in regard to correct detections. They did, however, emerge in an interaction with sensory modality in terms of the frequency of false alarms. Errors of commission were greater in the asynchronous event than in the synchronous event condition but only when observers monitored for visual stimuli. Restriction of the false alarm effects associated with the event schedule to visual monitoring may be a consequence of differential coupling inherent in the visual and auditory modalities. As described by Hatfield and Loeb (1968), observers in visual vigilance tasks are free to make head and eye movements that are incompatible with observing the display. Therefore, observers in visual tasks are loosely tied to or loosely coupled to the display in that they are free to orient away from it. In contrast, observers in auditory tasks are usually linked to the source of stimulation, either through earphones, as in this study, or through an enveloping sound field. Thus, their physical orientation does not determine their receptiveness for stimulation and observers are more closely coupled in auditory vigilance tasks. The unpredictability of the time of arrival of the events to be scanned in the asynchronous event condition, combined with a greater likelihood of inappropriate physical observing behavior when observers monitored for visual stimuli, may have resulted in the modality-specific differences in false alarms between the asynchronous and synchronous event schedules. To the extent that asynchronous event schedules appear in military-related tasks, such as monitoring for the appearance of stimuli that may represent enemy threats, the present results suggest that when possible, audition might be the mode of choice for information display.

The sensory linkage in performance associated with the event schedule was mirrored in the blood flow data. Consistent with expectation, blood flow was higher for the asynchronous as compared to the synchronous condition. However, as in the case of the false alarm performance measure, this effect appeared primarily in the context of visual stimuli. In the case of auditory stimuli, blood flow was also greater in the asynchronous than in the synchronous condition but only during the initial periods of watch.

As in the earlier vigilance/blood flow studies (Matthews et al., 2004; Warm & Parasuraman, in press), hemispheric differences in blood flow also were observed in this investigation. Overall blood flow was greater in the right than in the left cerebral hemisphere and the differences in CBF between the two event schedules were not the same in the two hemispheres. The right hemisphere showed a consistent asynchronous event advantage in CBF, while in the left hemisphere, blood flow in the asynchronous condition declined more rapidly over time than in the synchronous condition so that by the end of the session, there was a CBF advantage in favoring the latter event schedule. These hemispheric effects together with the lack of hemispheric differences in the general decline in CBF over time suggest that while an overall right hemispheric system may be involved in the functional control of vigilance (Parasuraman, et al., 1987; Warm & Parasuraman, in press), sustained attention is not completely lateralized.

Consequently, a cooperative interaction model (Allen, 1983; Hoptman & Davidson, 1994; Warm et al., 1976) may best describe the role of cerebral functioning in regard to the event schedule factor and the effects of time on task. The absence of completely lateralized effects in vigilance is consistent with findings reported in our initial progress report last year (Matthews, et al., 2004; and with Hellige's (1993) proposal that even relatively simple tasks require the coordination of several information processing subsystems.

Work Completed at Georgia State University

For all of the studies summarized here, participants responded to stimuli presented via the Watchkeeper task described in the Year-1 progress report. The Watchkeeper task was inspired by the demands faced by a sentry or other individual who must maintain vigilance on a field of view, detect the presence of persons who may or may not be threats, and shoot accurately when threats are presented. The Watchkeeper task was modeled after the marksmanship range at the Aberdeen Proving Grounds. As illustrated in the accompanying figure, a grassy field, complete with trees and hills, is projected as the stimulus background in front of participants (see figure). The display is projected on a screen, and occupies approximately 45 degrees of visual angle (approximately 2.3 meters diagonal). The participant must monitor this scene for 28 minutes, searching for threat images (orange rectangles) that appear infrequently from behind the trees or over the hills and then disappear again behind the blinds. Nonthreat images (blue rectangles) appear more frequently, but with comparable stimulus locations and display durations. The targets are scaled so that those that distance and size covary as they would in a natural display. Participants see threat or no threat stimuli with an event rate averaging 10/minute. The ratio of nonthreat threat stimuli is 80%:20%.

To respond to these images, participants use one of three manipulanda (assigned as a between-subjects manipulation). Some participants use the computer mouse to click on the threat images when they appear. Other participants respond with a replica of a 9-mm handgun, modified by LaserShot, Inc. to produce a laser blip on the screen when fired. This laser spot is interpreted by our software as a mouse click, such that the time and location of each shot is recorded. The third available response manipulandum is a LaserShot-modified rifle. The rifle was similarly modified so as to simulate a mouse click on the screen. The task and response apparatus, including the head-mounted TCD sensors, are illustrated in the figure on the right. No

response was required to the nonthreat images.

Several measures of attention (or, alternatively, of inattentiveness) are available from the Watchkeeper task. The first measure is reflected in the signal-detection decisions whether or not to shoot at a particular stimulus. Hit rate (the proportion of times a target appeared on the screen and a response was made) or its converse (miss rate, or the proportion of times a target appeared without a shot being produced) are primary indicators of attention. False-alarm rate (shots fired following the presentation of nontarget images) supply information about the bias and sensitivity of participants making the shoot/don't-shoot decisions.

The latency to respond to a target stimulus is a second measure of attention in the Watchkeeper task. Shots fired during target-stimulus presentations are timed, with the underlying assumption that faster responses reflect more intense attentiveness to the task.

Marksmanship accuracy is measured by the distance between the target-center and the location of a shot on the screen. Generally speaking, of course, individuals differ in marksmanship accuracy, and accuracy would be expected to improve with practice (as we found in Year-1 of this project). To calibrate marksmanship accuracy and to provide initial practice for the participants (thereby minimizing the amount of improvement in accuracy we obtained during an experimental session), each participant completed a preliminary task before Watchkeeper requiring a series of targets appearing all around the screen to be shot.

Thus, we operationalized inattention as an increased probability of missing target presentations on the Watchkeeper task, as longer response latencies when responses are made to target images, and as decreased marksmanship accuracy as a function of time-on-task.

GSU Experiments

1. Compared TCD and Eye-movement indicators of inattention (Experiment 1)

   TCD is an intriguing measure, of course, but it is not the only psychophysiological measure that might reflect variations in attention. One study described in the original proposal compares TCD with occulomotor and pupillometric indicators of inattention. Unfortunately, pilot studies revealed the impossibility of using the head-mounted TCD apparatus on participants simultaneously with the head-mounted ISCAN eye-tracker/pupillometer that we have available at GSU. The two apparatus could not be positioned simultaneously on a participant so to allow stable detection of cerebral blood flow (i.e., the signals could not be found and, more frequently, the transducers could not be locked securely into position), and the eye-tracker moved spuriously causing calibration errors. Consequently, we have employed two research strategies for examining the relation between measures of inattention from TCD and from the eye-tracker. First, we have upgraded our table-mounted eye-tracker/pupillometer. When it is returned from ISCAN, we will be able to monitor eye movements and changes in pupillary response remotely (i.e., without requiring the participant to wear another

apparatus on her/his head). In this way, we can simultaneously acquire psychophysiological measures from the eye and the brain.

Second, we examined participants in a between-groups design as they performed the Watchkeeper vigilance task. One group of 14 participants performed the task while wearing the ISCAN eye-tracker/pupillometer. The second group of 17 participants performed the Watchkeeper task while cerebral blood flow was monitored using the TCD system. The preliminary results of this study were presented in a poster at the Society for Computers in Psychology.

For the eye-tracker group of participants, Watchkeeper performance was analyzed as a function of the following independent variables: mean pupil dilation, trend in pupil dilation, mean fixation duration, trend in fixation duration, visual scanning distance (the amount the eyes moved prior to presentation of a threat or no threat image), mean saccade distance, blink rate, and trend in blink rate.

The results indicated a decrement in Watchkeeper performance across the vigil, reflected as a drop in target hit rate (shots when a target is present), an increase in response time, and a decrease in marksmanship accuracy across watch periods. Trends for hit-rate and response time were linear, whereas the marksmanship measure

	Min 1-7	**Min 8-14**	**Min 15-21**	**Min 22-28**
Hit rate (mean percent of targets to which the participant responded)	90%	88%	85%	82%
Response time (mean msec from presentation of target to first response)	1211	1300	1343	1383
Marksmanship error (mean distance from target to shot, in pixels)	95	91	119	130
Mean TCD during hits (left hemisphere) Mean TCD during hits (right hemisphere)	58.13 56.83	54.78 54.93	55.32 53.77	55.18 54.54
TCD during misses (left hemisphere) TCD during misses (right hemisphere)	57.47 59.88	57.08 57.27	54.37 53.31	53.97 53.46
NOTES: “hits” and “misses” refer to signal detection outcomes, not marksmanship outcomes. With respect to marksmanship, a distance of 100 translates a shot error of approximately 3 cm on both the horizontal and vertical axis				

For the TCD group, neither left cerebral blood flow nor right cerebral blood flow were found to differ significantly between Watchkeeper hits and misses ($p > .10$ for both *t*-tests). However, speed of blood flow measures were significantly correlated with variations in Watchkeeper response time and marksmanship accuracy, although the variance accounted for by these prediction was quite small. The speed of blood flow to the left and right hemispheres correlated with variations in response time (i.e., the latency to fire the weapon after presentation of a target stimulus) $r = -.13$ and $-.07$, respectively. The speed of blood flow to the right hemispheres correlated with variations in

marksmanship accuracy (i.e., the distance between the location of a shot from the firearm and the center of the target stimulus) $r = .09$ (left hemisphere blood flow was not significantly correlated with this measure).

Interestingly, a very different pattern of results was obtained from the eye-tracker group. Pupillometric and occulomotor measures did not correlate significantly with marksmanship accuracy or Watchkeeper response time; however, there were significant difference in two of the eye-movement measures in the comparison of signal-detection hits versus misses. That is, they eyes moved significantly more and the pupils were significantly more dilated on trials in which the participants responded to targets than on trials in which the participants ignored targets.

These results show that TCD and eye-movement are associated with different, potentially complementary measures of inattention. It was not possible from these data to examine the combined predictions from TCD and eye-movement indices, because the data were collected on a between-groups basis. However, this study will be replicated in Year-3 using the desk-mounted eye tracker to allow us to determine whether TCD and eye-movement together contribute additively to the prediction of inattention.

2. Completed data collection for TCD and Watchkeeper performance (Experiment 2)

A more important finding than the one described above would involve determination of how far in advance of the presentation of a target stimulus could we predict whether a participant will attend to the target. That is, does TCD provide a means for indicating when a participant is going to be inattentive? This question was the focus of the main study proposed in the grant and conducted this year. Data collection was completed for this study during Year-2. Data analyses, which are necessarily slow and complex in that they involve an iterative series of predictions at time N, N-1, N-2 and so forth, are ongoing. Preliminary results from these data analysis are described below.

To date, we have examined the degree to which Watchkeeper performance can be predicted from TCD measures collected in the 4-second interval immediately preceding the presentation of a target stimulus (at time T), and from the trend between those T-4 measures and the T-8 measures for the interval before that. Not surprisingly (given the results from Experiment 1 described above and given that the binary distribution of hits versus misses produces little variance to predict), no combination of TCD measures has yet been found to predict when a target would be missed (i.e., produce no response). However, TCD has been shown significantly to predict variations in response time and marksmanship error, although the proportion of variance accounted for is very small (all $r^2 <= .03$ so far). For example, response time is significantly predicted by T-4 blood flow in the left cerebral hemisphere ($r = -.13$, $p < .01$), and this prediction is not improved when right cerebral blood flow measures or the trend from the T-8 measures is added to the regression. Conversely, variations in marksmanship accuracy are significantly

predicted by T-4 TCD measures from the right hemisphere ($r = .09$, $p < .01$). Again, no other measure calculated to date augments this regression equation significantly.

In ongoing analyses, we are analyzing more chronic indicators of mental activity (e.g., TCD measures from the 30-seconds or minute preceding a target). Critically, we also must deconfound TCD during previous intervals with possible target presentations during those previous intervals. That is, we will examine the combined prediction of TCD and time-since-last target to provide a finer-grained analysis of inattention.

3. Initiated data collection for a between-groups study of inattention and TCD (Experiment 3)

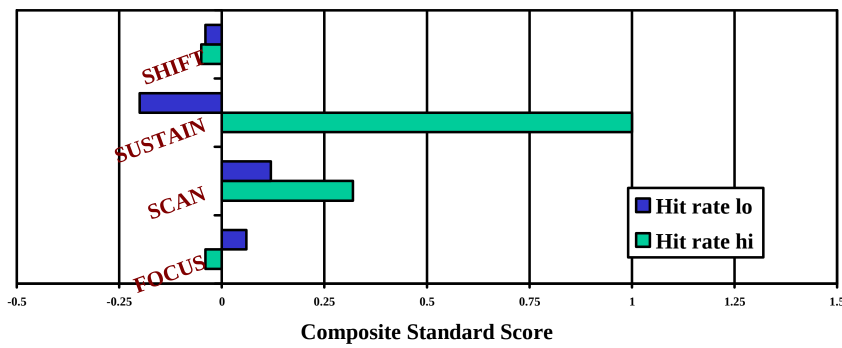
One of the major research achievements during Year-2 was learning how to collect the TCD data effectively and efficiently. It is difficult to find a suitable window for the transducer with some participants; indeed, we were unable to obtain a consistent signal at all (after 90 minutes of trying) with 8% of the undergraduates we tested. The more common scenario is that we obtained a good signal for hemovelocity on one side of the brain but a poor signal from the other cerebral hemisphere. This occurred for about 22% of the participants tested, although both this outcome and the “no-signal” outcome became less likely the more experience we had with the TCD device.

Rather than discarding the data from participants who, for whatever reasons, could not be tested with reliable TCD signals from both cerebral hemispheres, these participants have been included in a between-groups study. The undergraduates for whom only a left-hemisphere signal was obtained will be compared to the undergraduates for whom only a right-hemisphere signal was available. Data analysis for this study will proceed once there are adequate numbers in each group, and once the results from Experiment 2 (above) indicate what we should be looking for with the opportunistic between-groups sample.

4. Began data collection on the attention profiles of Watchkeeper performance.

One of the studies described in the original proposal is a large-N investigation of vigilance on the Watchkeeper task and its relation to individual differences in attention abilities as assessed by the ASAP (Assessment Software for Attention Profiles) battery. ASAP provides independent measures of the ability to focus attention or to concentrate, to scan attention or to orient, to shift or shift attention, and to sustain attention or to remain alert. In addition to the assessment tasks that comprise the ASAP battery (including a Stroop task, a visual search task, a continuous-performance task, and other measures of attention focusing, scanning, and sustaining), participants were tested on the Attention Network Test (ANT) devised by Michael Posner and colleagues (Posner, 1993; Robertson, 2004). ANT also provides uncorrelated measures of the three dimensions or factors of attention (which Posner and colleagues prefer to call executive attention, orienting, and alerting).

To date, 51 participants have completed the ASAP battery in addition to performing the Watchkeeper task while being monitored with TCD. The target number of participants for this study is at least 80, so data collection will likely conclude in January. As illustrated in the figure below, preliminary analysis of the ASAP data suggest that participants in the bottom quartile for hit rate (i.e., those participants who fail to respond most often to the presentation of a target image) differ from the top quartile for hit rate (those participants who are least likely to miss the presentation of a target) primarily on the skill of attention-sustaining, with no significant differences apparent for attention-focusing and attention-scanning. Although these results are intuitive, it must be emphasized that they are preliminary, reflecting only about half of the measures available from ASAP.



5. Began data collection for TCD, stress and vigilance study (Experiment 4)

    As was described in the original proposal, we are interested in the effects of stress on vigilance performance, TCD measures, and cognitive outcomes. Accordingly, we began collecting two indicators of stress: saliva samples (for assay of the stress-related hormone cortisol) and self-report (using the Dundee Stress State Questionnaire, or DSSQ). To date, 23 participants have been tested in this study, and none of those assays have been analyzed to date. Data collection with the DSSQ and with salivary cortisol will be a focus of investigation in the first part of Year-3.

<u>Plans for Funding Year-3 (all tasks include TCD measures)</u>

1. Complete data collection for the Watchkeeper + ASAP study.

2. Continue data collection for the Watchkeeper and stress study.

3. Begin and complete data collection for the Watchkeeper + U.C. tasks.

4. Begin and complete data collection for the second criterion task, a continuous decision-making task requiring participants to make a series of shoot/don't-shoot judgments under conditions of high threat.

5. Begin and complete the TCD / eye-tracker within-subject follow-up study.

Key research accomplishments

- The results of UC- Study I Confirm that transcranial Doppler sonography (TCD) may be used to measure meaningful individual differences in cerebral blood flow. Sensitivity of blood flow factors to psychological factors has been demonstrated.
- UC-Study 1 also demonstrates the potential of a multi-phase approach to diagnosis of the operator's functional status and fitness to perform tasks requiring sustained attention. Subjective and physiological measures, including TCD indices, derived from a short task battery were predicative of performance on a subsequent vigilance task.
- UC-Study 1 demonstrates that use of multiple diagnostic indices and building regression models may enhance accuracy of prediction. Practically useful predictive validity may be obtained by integrating multiple measures from a short test battery may be used to measure meaningful individual differences in cerebral blood flow.
- UC-Study 2 verifies the utility of TCD in monitoring performance on auditory as well as visual sustained attention tasks.
- UC-Study 2 provides strong evidence that while sensory difference in vigilance are important, common mechanisms control vigilance performance in the visual and auditory modes.
- UC-Study 2 indicates that temporal uncertainty in the time of appearance of events to be scanned for possible critical signals promotes errors of commission (false alarms) when monitoring for visual but not for auditory signals.
- UC-Study 2 confirms that there is a close tie between the vigilance decrement and cerebral blood flow.
- UC-Study 2 confirms the likelihood of a right hemisphere system in the functional control of vigilance performance but also indicates that vigilance performance is not completely lateralized in terms of the effects of temporal uncertainty in the event schedule and the vigilance decrement.
- A methodology has been established for exploring the generality of findings from earlier studies. Specifically, Study 3 (in progress) is examining whether the physiological and

psychological indices used in Study 1 are also predictive of performance on a cognitive vigilance task, imposing high demands on working memory.

- Findings continue to confirm the utility of resource theory as a theoretical framework for understanding workload effects on vigilance and blood flow. The theory may also provide a basis for investigating effects of workload as moderator factor in building diagnostic models of performance, as explored in UC- Study 1.
- Studies from GSU point to critical hemispheric differences in regard to detection and marksmanship on a simulated sentry task. Response time to target detection appears to be a bilateral function since that measure varies inversely with blood flow in each hemisphere. However, marksmanship accuracy is apparently a right hemisphere function since blood flow in the right hemisphere correlated positively with accuracy but blood flow in the left hemisphere was not correlated with that measure.
- Studies from GSU indicate that cerebral blood flow and eye movement are associated with different, potentially complementary, measures of inattention.
- Studies from GSU suggest that cerebral blood flow may be useful in predicting when observers will be inattentive on the simulated sentry task and for predicting marksmanship error on that task

• REPORTABLE OUTCOMES

Journal articles

Helton, W.S., Hollander, T.D., Warm, J.S., Matthews, G., Dember, W.N., Wallaart, M., Beauchamp, G., Parasuraman, R., & Hancock, P.A., (2005). Signal regularity and the mindlessness model of vigilance. *British Journal of Psychology, 96*, 249-261.

Book chapters

Helton, W.S., Shaw, T.S., Warm, J.S., Matthews, G., Dember, W.N., & Hancock, P.A. (2004). Demand transitions in vigilance: Effects on performance efficiency and stress. In D.A. Vincenzi, M. Mouloua, & P.A. Hancock (Eds.), *Human performance, situation awareness, and automation: Current research and trends.* HPSAAII Vol.(pp.258-262). Mahwah, NJ: Erlbaum.

Tripp, L.D., & Warm, J.S. (in press). Transcranial Doppler sonography. In R. Parasuraman & A.M. Rizzo (Eds.), *Neuroergonomics: The brain at work.* Cambridge, MA: MIT Press.

Warm, J.S., & Parasuraman, R. (in press). Cerebral hemovelocity and vigilance performance. In R. Parasuraman & A.M. Rizzo (Eds.), *Neuroergonomics: The brain at work.* Cambridge, MA:MIT Press.

Unpublished conference presentations

Funke, G., Matthews, G., Emo, A.K., & Warm, J.S. The effects of partial-vehicle automation on driver mood and performance in a simulated winter drive. Ninety-seventh Annual Meeting of the Southern Society for Philosophy and Psychology, Durham, NC, April 2004.

Matthews, G., & Emo, A.K., Funke, G. J. A short version of the Dundee Stress State Questionnaire. Twelfth Meeting of the International Society for the Study of Individual Differences, Adelaide, Australia, July 2005.

Matthews, G., Warm, J.S., Proctor, C.A., Parsons, K.S., Reinerman, L.E., Langheim, L., & Tripp, L.D. Individual differences in cerebral blood flow during sustained performance. Twelfth Meeting of the International Society for the Study of Individual Differences, Adelaide, Australia, July 2005.

Matthews, G. The transactional model of driver stress and fatigue and its implications for driver training. Keynote Address: Second International Conference in Driver Behaviour and Training, Edinburgh, November 2005.

Washburn, D. A., Barrett, N. James, F., Philipp, M., Hoffman, M., Elliott, L., Petridis, A., Kim, A., Henderson, B., Berzofsky, S., & Hill, M. (2005, November). A Comparison of Transcranial Doppler and Eye-Movement Apparatus for the Study of Inattention. Poster presented at the annual meeting of the Society for Computers in Psychology. Toronto, ON.

Washburn, D. A., James, F. & Taglialatela, J. (2005, May). Individual Differences in Attention Skills and Temporal Variations in Threat-Detection Performance. Poster presented at the meeting of the American Psychological Society, Los Angeles, CA.

Warm, J.S., Matthews, G., Szalma, J., Hancock, P.A., & Parasuraman, R. (2005, July). Cerebral hemodynamics and vigilance performance. Eleventh International Conference on Human-Computer Interaction. Las Vegas, NV

Published conference presentation

Funke, G.J., Matthews, G., Warm, J.S., Emo, A., & Fellner, A.N. (2005). The influence of driver stress, partial-vehicle automation, and subjective state on driver performance. In *Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting*, pp. 936-940. Santa Monica, CA: Human Factors and Ergonomics Society.

Ungar, N.R., Matthews, G., Warm, J.S., Dember, W.N., Thomas, J.K., Finomore, V.S., & Shaw, T.H., (2005). Demand transitions and tracking performance efficiency: Structural and strategic models. In *Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting*, pp. 1523-1527. Santa Monica, CA: Human Factors and Ergonomics Society.

Invited address:

Warm, J.S. (2005, May). Cerebral hemodynamics and vigilance performance. Institute for Ergonomics, The Ohio State University.

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CONCLUSIONS

Manipulation checks in UC-Study #1 showed that the task procedures used in the University of Cincinnati studies provided a suitable platform for investigating predictors of performance in a broadly stressful setting. Both the short task battery and the vigilance task elicited increased subjective distress, relative to baseline, and the vigilance task also provoked a large decline in task engagement, corresponding to a state of fatigue. The tasks also imposed a high level of workload, and the vigilance task produced declines in performance and blood flow comparable to those seen in previous studies. Individual differences in blood flow were found to be reliable and meaningfully inter-related across tasks and hemispheres. The 'phasic' blood flow responses to the short tasks were related to task processing requirements largely as expected. Magnitude of these responses also predicted blood flow during the subsequent vigilance task. The data also show the importance of assessing task-induced responses; baseline blood flow measurements, although reliable, were generally unrelated to other criteria.

The data also show some correlations between different indicator variables, as hypothesized. Baseline task engagement predicted magnitude of the phasic blood flow response. Positive associations between blood flow and use of task-focused coping strategies were also established. Task engagement, task-focused coping and blood flow increments may all reflect a common "energization" for processing response, as discussed originally by Kahneman (1973). By contrast, subjective distress and worry appeared to be largely unrelated to blood flow, suggesting that TCD does not directly index emotional stress. Salivary cortisol was only weakly related to other psychophysiological indicators, but some significant, small associations between cortisol response and blood flow were obtained.

All of the indicator variables showed some potential as predictors of performance. Subjective task engagement, phasic blood flow response and cortisol response to the short task battery all correlated with some aspect of vigilance performance, although correlation magnitudes were typically modest. By contrast, the best concurrent predictors of performance – i.e., those derived from the vigilance task itself – were rather different. High task-focused coping, and low post-task distress and avoidance coping were the best subjective predictors. Because the correlations concerned are cross-sectional, it is possible that they reflect effects of performance on subjective state, rather than causal effects of subjective state. Surprisingly, blood flow was unrelated to performance in the cross-sectional data; the phasic blood flow response appears to be a better indicator than concurrent blood flow assessment.

The regression analyses suggested that the modest bivariate associations may be boosted by identifying multiple independent predictors, although the predictor sets vary for different performance measures. Correct detections relate most substantially to task engagement, and false positives to blood flow and salivary cortisol. For both performances indices, however, evidence was obtained to suggest that the relationship between blood flow and vigilance performance varies with perceived workload, such that blood flow may be more predictive of performance when workload is low. Accommodating the moderator effect of workload may enhance prediction.

To date, all of the research on the relation between cerebral blood flow and vigilance performance has been conducted with visual tasks. For both theoretical and practical reasons, it would be convenient to assume that the blood flow/vigilance relation also exists for auditory

vigilance tasks, but such an assumption would not necessarily be warranted given the presence of substantial sensory differences in vigilance performance. Our research, however, as described in UC-Study #2, clearly indicates that the close parallel between vigilance performance and cerebral blood flow noted in visual tasks may appear to a similar degree with auditory tasks—in both cases, linear declines in signal detections and false alarms over time are accompanied by a linear decline in cerebral blood flow. These results, obtained with blood flow measures secured from the same cerebral arteries support the view that while stimulus-specific sensory factors are important in vigilance, within limits, vigilance is a general characteristic of the observer. On an applied level, they also indicate that declines in cerebral blood flow may be useful in indexing a temporal decline in the effectiveness of military personnel performing auditory as well as visual monitoring tasks.

The findings obtained at the University of Cincinnati regarding the parallel between blood flow and sustained attention and the predictive validity of the blood flow measure with regard to vigilance performance have been supported in research conducted at Georgia State University using a simulated sentry task. As in the Cincinnati studies, those at Georgia State have also shown that blood flow covaries with performance efficiency on a simulated sentry task, and that blood flow measures obtained at an early point in time predict performance efficiency at a later time point. The studies the Georgia State studies also point to critical hemispheric differences in regard to detection and marksmanship on the simulated sentry task. Response time to target detection appears to be a bilateral function, since that measure varies inversely with blood flow in each hemisphere. However, marksmanship accuracy is apparently a right hemisphere function since blood flow in the right hemisphere correlated positively with accuracy but blood flow in the left hemisphere was not correlated with that measure.

REFERENCES

Aaslid, R. (1986). Transcranial Doppler examination techniques. In R.Aaslid,(Ed.),*Transcranial Doppler Sonography* (pp. 39-59). New York: Springer-Verlag.

Allen, M. (1983). Models of hemispheric specialization. *Psychological Bulletin, 93*, 73-104.

Ballard, J.C. (1996). Computerized assessment of sustained attention: A review of factors affecting vigilance performance. *Journal of Clinical and Experimental Neuropsychology,18*, 843-863.

Calvert, G.A., Spence, C., & Stein, B. (Eds.). (2004). *The handbook of multisensory processes.* Cambridge, MA: MIT Press

Davies, D.R., & Parasuraman, R. (1982). *The psychology of vigilance*. London: Academic Press.

Dickerson, S.S., & Kemeny, M.E. (2004). Acute stressors and cortisol responses: A theoretical integration and synthesis of laboratory research. *Psychological Bulletin, 130*, 355-391.

Hatfield, J.L., & Loeb, M. (1968). Sense mode and coupling in a vigilance task. *Perception & Psychophysics, 4*, 29-36.

Hellige, J.B. (1993). *Hemispheric asymmetry: What's right and what's left?* Cambridge, MA: Harvard University Press.

Hitchcock, E., Warm, J.S., Matthews, G., Dember, W.N., Shear, P.K., Tripp, L., Mayleben, D.W., & Parasuraman, R. (2003). Automation cueing modulates cerebral blood flow and vigilance in a simulated air traffic control task. *Theoretical Issues in Ergonomics Science, 4,* 89-112.

Hoptman, M.J., & Davidson, R.J. (1994). How do the two cerebral hemispheres interact. *Psychological Bulletin, 116*, 195-219.

Loeb, M., Behar, I., & Warm, J.S. (1966). Cross-modal correlations of perceived duration of auditory and visual stimuli. *Psychonomic Science, 6*, 87.

Matthews, G., Joyner, L., Gilliland, K., Campbell, S.E., & Huggins, J., & Falconer, S. (1999) Validation of a comprehensive stress state questionnaire: Towards a state 'Big Three'? In I. Mervielde, I.J. Deary, F. De Fruyt, & F. Ostendorf (Eds.), *Personality psychology in Europe* (Vol. 7), pp. 335-350. Tilburg: Tilburg University Press.

Matthews, G., & Campbell, S.E. (1998) Task-induced stress and individual differences in coping. In *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting*, pp. 821-825. Santa Monica, CA: Human Factors and Ergonomics Society.

Matthews, G., Campbell, S.E., Falconer, S., Joyner, L., Huggins, J., Gilliland, K., Grier, R., & Warm, J.S. (2002). Fundamental dimensions of subjective state in performance settings: Task engagement, distress and worry. *Emotion, 2*, 315-340.

Matthews, G., & Davies, D.R. (1998) Arousal and vigilance: The role of task factors. In R.B. Hoffman, M.F. Sherrick, & J.S. Warm (Eds.), *Viewing psychology as a whole: The integrative science of William N. Dember*, pp. 113-144. Washington, DC: American Psychological Association.

Matthews, G., Warm, J.S., Dember, W.N., Mizoguchi, H., & Smith, A.P. (2001) The common cold impairs visual attention, psychomotor performance and task engagement. In *Proceedings of the Human Factors and Ergonomics Society 45th Annual Meeting*, pp. 1377-1381. Santa Monica, CA: Human Factors and Ergonomics Society.

Matthews, G., Warm, J.S., & Washburn, D. (2004). *Diagnostic Methods for Predicting Performance Impairment Associated with Combat Stress*. Annual report for U.S. Army Medical Research and Materiel Command (award # W23RYX-3106-N605).

Maxwell, S.E., & Delaney, H.D. (2004). *Designing experiments and analyizing data: A model comparison perspective (2nd ed.)* Mahwah, NJ: Erlbaum

Oldfield, R. (1971). The assessment and analysis of handedness: The Edinburgh inventory *Neuropsychologia*, *9*, 97-113.

Parasuraman, R., Warm, J. S., See, J. E. (1998). Brain systems of vigilance. In R. Parasuraman (ed.), *The attentive brain* (pp. 221-256). Cambridge, MA: MIT Press.

Posner, M.I., (1993). Interaction of arousal and selection in the posterior attention network. In A. Baddeley & L. Weisenkrantz (eds.), *Attention, selection, awareness and control (pp.390-405).*Oxford, UK: Clarendon Press.

Robertson, I. (2004). Examining attentional rehabilitation. In M.I. Posner (Ed.), *Cognitive neuroscience of attention* (pp. 407-419). New York: Guilford Press.

Scerbo, M.W., Warm, J.S,, & Fisk, A.D. (1986). Event asynchrony and signal regularity in sustained attention. *Current Psychological Research & Reviews*, *5*, 335-343.

Scerbo, M. W., Warm, J. S., Doettling, V. S., Parasuraman, R., Fisk, A. D. (1987). Event Asynchrony and Task Demand in Sustained Attention. In L.S. Mark, J.J. Warm, & R.L. Huston (Eds.), Ergonomics and human factors: Recent research (pp. 33-39). New York: Springer-Verlag.

See, J.E., Howe, S.R., Warm, J.S., & Dember, W.N. (1995). Meta-analysis of the sensitivity decrement in vigilance. *Psychological Bulletin*, *117*, 230-249.

Stevens, S.S. (1959). Cross-modality validation of subjective scales for loudness, vibration, and electric shock. *Journal of Experimental Psychology*, *57*, 201-209.

Stroobant, N., & Vingerhoets, G. (2000). Transcranial Doppler Ultrasonography Monitoring of Cerebral Hemodynamics During Performance of Cognitive Tasks: A Review. *Neuropsychology Review*, *10*, 213-231.

Szalma, J.L, Warm, J.S., Matthews, W.N., Weiler, E. M., Meier, A., Eggemeier, F. T.. (2004), Effects of sensory modality and task duration on performance, workload, and stress in sustained attention. *Human Factors*, *46*, 219-233.

Tripp, L.D., & Warm, J.S. (in press). Transcranial Doppler sonography. In R. Parasuraman & A.M. Rizzo (Eds.), *Neuroergonomics: The brain at work.* Cambridge, MA: MIT Press.

Ungar, N.R., Matthews, G., Warm, J.S., Dember, W.N., Thomas, J., Finomore, V., & Shaw, T. (2005). Demand transitions and tracking performance efficiency: Structural and strategic models. In *Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting*, pp. 1523-1527. Santa Monica, CA: Human Factors and Ergonomics Society.

Walk., R.D., & Pick H.L. (1981). *Intersensory perception and sensory integration.* New York: Plenum.

Warm, J.S. (1993). Vigilance and target detection. In B.M. Huey & C.D. Wickens (Eds.),*Workload transition: Implications for individual and team performance.* Washington, DC:National Academy Press

Warm, J.S., & Jersion, H.J. (1984). The psychophysics of vigilance. In J.S. Warm (ed.), *Sustained attention in human performance* (pp. 15-59). Chichester, UK: Wiley.

Warm, J.S. & Matthews, G. (2003, June). *Cerebral Hemodynamics and Vigilance Performance.*

Paper presented at the U.S. Army Military Operational Research Program meeting on Cognitive, Psychophysiological, and Behavioral Monitoring for Military Field Applications, Cincinnati, OH**.**

Warm, J.S., & Parasuraman, R. (in press). Cerebral hemovelocity and vigilance. In R. Parasuraman & A.M. Rizzo (Eds.), *Neuroergonomics: the brain at work.* Cambridge, MA: MIT Press.

Warm, J.S., Schumsky, D.A., & Hawley, D.K. (1976). Ear asymmetry and temporal uncertainty in sustained attention. *Bulletin of the Psychonomic Society*, *7*, 413-416.